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The geothermal exploration of Campanian volcanoes: Historical review and future development

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ABSTRACT

Since Roman time, the heat produced by Neapolitan volcanoes was an appeal for people living in and outside the area, for the fruition of the famous thermal baths. This very large area, which spans from Campi Flegrei and Ischia calderas to Somma-Vesuvius volcano, is characterized by high temperature at shallow depth and intense heat flow, and is yet utilized for the bathing and spa treatment industry, while only in the middle of the 20th century a tentative of geothermal exploitation for energy production was performed. Pioneering researches of geothermal resource were carried out in Campanian region since 1930, until 1985, during which a large amount of geological data were collected. In this paper, we make for the first time a review of the history of geothermal explorations in the active Campanian volcanic area. By the analysis of a great amount of literature data and technical reports we reconstruct the chronology and the main information of the drillings performed since 1930 by the SAFEN Company and successively in the framework of the ENEL-AGIP Joint Venture for geothermal exploration. The available data are utilized to correlate the temperatures measured within the deeper wells with the possible sources of geothermal heat in the shallow crust, down to about 8–10 km of depth. Finally, we assess the geothermal potential of the hottest areas, Ischia Island and Campi Flegrei, which have shown the best data and favorable physical conditions for a reliable, and cost-effective, exploitation for thermal and electric purposes.

Contents

1. Introduction

The geothermal heat supplied by the active volcano districts of the Campania region (Fig. 1) was an appeal since Roman time, when the fruition of famous thermal baths of Ischia island, Baia and Lucrino (Campi Flegrei) become a custom for people living in and outside the area (Fig. 2). Since that time on, visitors to Ischia and Campi Flegrei would have been lured and connected to the development of the bathing and spa treatment industry [1]. The industrial revolution, started on the XVII century, arose the needs of raw material for energy production, coal in a first times and oil in recent times. In this framework nowdays, the geothermal renewable energy can be considered, if easily available, a high value economic resource for thermal and electric energy production. Pioneering researches of geothermal resource were carried out in Campanian region since 1930. More recent researches were part of the National Energy Plan [2], aimed to better constrain the

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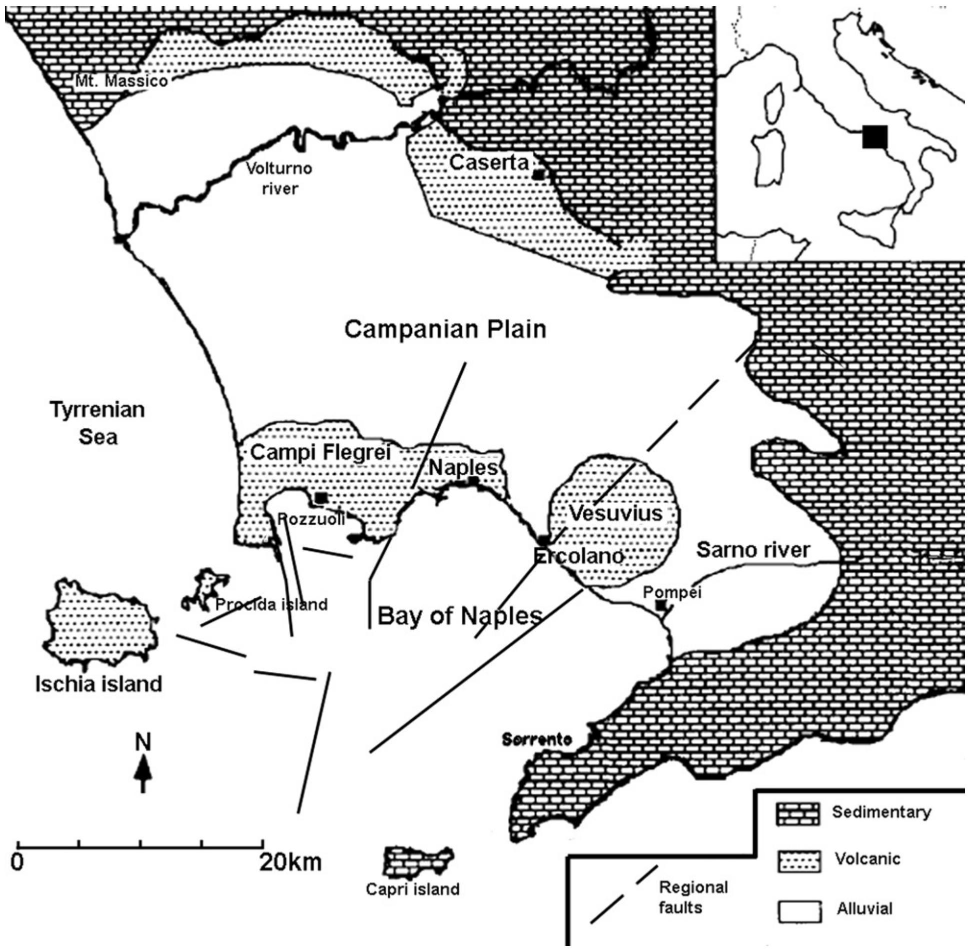

Fig. 1. The Campanian Plain and the active volcanoes area of Vesuvius, Campi Flegrei and Ischia, with main tectonic features.

geothermal potential in the volcanic district of Campania (Vesuvius, Campi Flegrei caldera and Ischia Island), and were supported by a Joint Venture between ENEL and AGIP Companies [3]. The exploration program was stimulated also by the interesting results on geothermal exploitation obtained at Larderello (Tuscany), since the early 1900 [4].

From 1930 to the mid 1980, a total of 117 wells for geothermal exploration were drilled down to a maximum depth of 3046 m (90 wells at Ischia, 26 at Campi Flegrei and 1 at Vesuvius). The results of such investigations were particularly encouraging at Campi Flegrei and Ischia, where elevated geothermal gradients were recorded, due to the presence of high enthalpy fluids ($T > 150\,^{\circ}$C) localized at shallow depths (hundred of meters) and both vapor and water dominated [3]. Despite these interesting results, the exploitation of the campanian geothermal resource was never started, mainly because, after the mid '1980s, the oil price was again very cheap, Italy was starting its first nuclear plan (abandoned in 1986 after the Chernobyl disaster) and there was not yet a real interest for renewable energy beyond simple economic considerations. The drilling program at Campanian volcanoes had stimulated not only the geothermal research for industrial application, but also the researches in the field of the volcanolgy. Important information such as temperatures of shallow crust, chemical rocks and fluids composition at depth and stratigraphy have been utilized for the reconstruction of the eruptive history of Vesuvius, Campi Flegrei caldera and Ischia and to constrain physical models of volcanic activity [14,36,58]. In recent time, the attention posed on the geothermal potential of the Campania region has been drawn back consequently to the approval of the "Campi Flegrei Deep Drilling Project" (CFDDP), in the framework of the International Continental Drilling Program (ICDP) (icdp-online.org).

In this paper we make a review of the history of geothermal researches of Campanian volcanoes, starting from the earlier volcanological studies at Vesuvius, Campi Flegrei and Ischia. We analysed the historical and scientific reasons which make this area of great interest for geothermal research; by the analysis of a great amount of literature data and technical reports. We reconstruct the chronology and the main information of the drillings performed since 1930 by the SAFEN Company and successively in the framework of the ENEL-AGIP Joint Venture for geothermal exploration [3]. Furthermore, the available data are utilized to correlate the temperatures measured within the deeper wells with the possible sources of geothermal heat in the shallow crust, down to about 8–10 km of depth. Finally, we assess the geothermal potential of Ischia and Campi Flegrei, which have shown the best data and favorable physical conditions for a reliable, and cost-effective, exploitation for thermal and electric purposes. Our studies are also preparatory for the realization of the "Campi Flegrei Deep Drilling Project" (CFDDP), approved by the International Continental Drilling Program (ICDP), and aimed to the understanding of the Campi Flegrei caldera dynamics and to the accurate geothermal resource assessment. This work also emphasizes the economic importance of the geothermal electric production, for Italy and mainly for the Southern regions, also as an alternative to the nuclear energy, after the abandon of the last resource decided by people in the recent general consultation (referendum).

Fig. 2. The old Roman thermal baths of Baia, in the Campi Flegeri volcanic area (photo: S. Carlino).

2. Geological settings

The Campania volcanic district is distinguished by the presence of three active volcanoes, Vesuvius, Campi Flegrei and Ischia within the Campania Plain. This structure, located on the Tyrrhenian margin, at the west of the Apennines, is characterized by a general tensional tectonic regime, with NE-SW and NW-SE regional faults systems, which produced faulted graben morphology of the carbonate basement. The structural depression is mainly filled by Plio-Quaternary volcanic rocks and sediments (Fig. 1). The Campania volcanoes are localized along the NE-SW and N–S regional faults, while the volcanism of this area seems to have started between 1 and 2 My ago [5–10]. The Campania volcanism is related to the tensional spreading process of the Tyrrenian basin, which produces the thinning of the crust and upwards migration of magma, generating an high heat flow of this area (>100 mW m^{-2}) [11–13] (Figs. 3 and 4).

The Southesternmost volcanic edifice, Mt. Somma–Vesuvius, is a strato-volcano consisting of a recent cone, Vesuvius, which evolved within the older Somma caldera [14,15] (Fig. 5). The volcanic complex rests on a sequence of Mesozoic and Cenozoic carbonates overlain by Miocene sediments of the Campanian Plain [16,17]. This thick sedimentary sequence has been found at a depth of about 1.5 km [18], and in seismic profiles in the Gulf of Naples at more than 3–4 km [6,19]. Volcanic activity in the area near Mt. Somma–Vesuvius extends from at least about 300 ky BP [18]. The volcanic history (on the basis of the outcropped products) started about 25 ky ago. This has been characterized by at least 4 plinian eruptions (Pomici di Base, 18–20 ky; Mercato, 8.7–9 ky; Avellino 3.5–3.7 ky; Pompei, 79 A.D.) spaced out by sub-plinian eruptions (Pomici Verdoline, 15–16 ky, Pollena, 472 A.D.; 1631 erution), minor eruptions (effusive-strombolian type) and by quiescent periods [14,20–22]. In recent time, from 1631 to 1944 the Vesuvius has undergone to a period of persistent activity, with well documented effusive to volcanian activity, which terminates with the 1944 moderate eruption [14,23]. During the history of the volcano, the magma reservoirs that fed the eruptive activity migrated from 8–9 km to 3–4 km depth [24]. Mt. Somma–Vesuvius is now quiescent, characterized by low fumarolic and seismic activity, and low temperature at depth. This state of repose has been associated with physical and chemical modifications affecting a cooling, residual magma body within the volcanic conduit [25]. The presence of such magma body is supported by the high rigidity, the magnetized character of the crust beneath the crater, extending

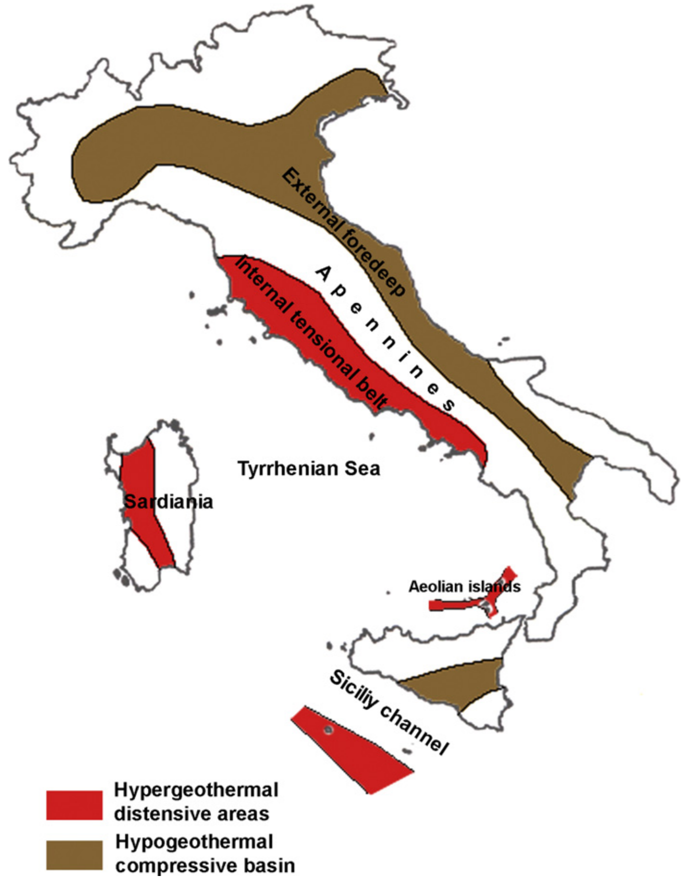

Fig. 3. Geothermal areas related to tensile and compressive tectonic processes. After AGIP (1987).

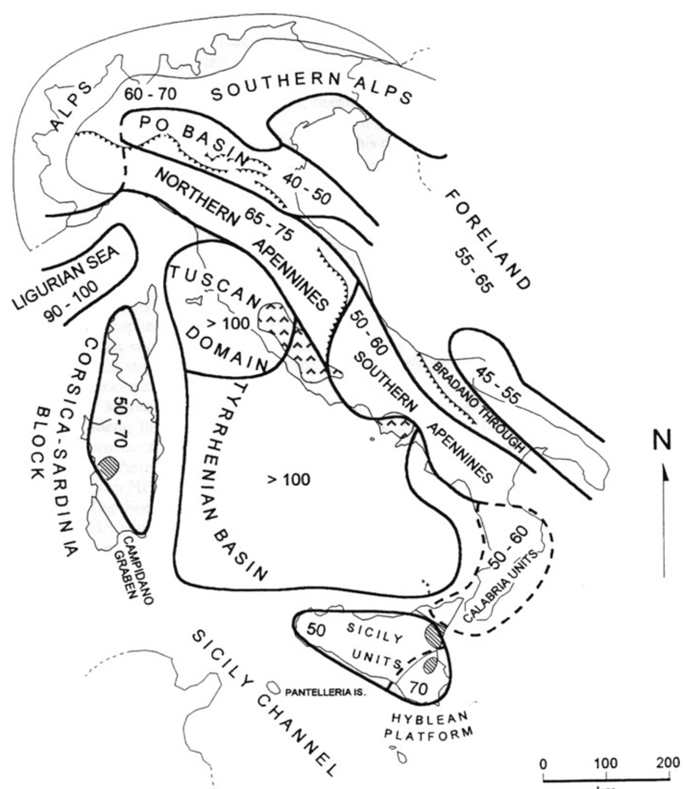

Fig. 4. Heat flow map of Italy.
After Della Vedova (2001).

Fig. 5. Somma-Vesuvius volcanic complex. The location of Trecase well is reported (red circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

down to about 5 km [26] and by geochemical data [27]. Seismic [28,29] and magnetotelluric surveys [30] indicate the presence of a large magma sill located under the volcano at about 8–10 km. Notably, a deeper magma chamber has also been proposed, perhaps extending to 20 km [31], where the crust–mantle boundary may be located [32,33]. A high velocity body dipping westward from 65 km down to 285 km was interpreted as a subducting plate within the mantle [31] which, also on the basis of deep seismicity (300 km) detected in the central Tyrrhenian Sea, is thought to indicate an actively subducting slab [34,35].

Located at the Northwestern limit of the Gulf of Naples, the Campi Flegrei caldera (CFc) is roughly 12 km wide, with its centre located in the Bay of Pozzuoli, about 15 km to the west of Naples. The current caldera shape is thought as the result of two large collapses, the first of which was probably related to the Campanian Ignimbrite (CI; 150–200 km^3 dense rock equivalent [DRE]; age, 39 ky BP), and the second to the Neapolitan Yellow Tuff (NYT; 40 km^3 DRE; age, 12–15.6 ky BP) eruptions [22,36–39] (Fig. 6). The volcanic activity has continued within the caldera, with phreatomagmatic eruptions and lava dome emplacement [36]. The last eruption occurred in 1538, with the formation of the Monte Nuovo crater, roughly in the centre of the caldera. Since Roman times, the CFc area has been characterized by slow subsidence, at a rate of about 1.1–2 cm y^{-1} [40,41], which has been interrupted by recurring phases of rapid uplift that are generally accompanied by intense seismicity. The study of sea-level markers on Roman coastal ruins has revealed historical ground movements, with a Roman market-place (Serapis) that was uncovered in A.D. 1750 in Pozzuoli being the subject of many studies (see for a review [40,42,43]). At least one well evident phase of uplift has been recognized to have occurred prior to the last Monte Nuovo eruption (A.D. 1538; 0.02 km^3 DRE) [44]. More recently, two phases of uplift have occurred, during 1970–1972 and 1982–1984, when the town of Pozzuoli was raised by 1.7 m and 1.8 m, respectively. During the 1982–1984 unrest episode, more than 15,000 shallow earthquakes (at 1–5 km in depth) with a maximum magnitude of 4.0 were recorded by the seismic stations of the Osservatorio Vesuviano [45], and the ground uplift occurred at an average rate of 0.3 cm d^{-1}. The last episode of unrest indicated the possibility of an imminent eruption, forcing the authorities to evacuate Pozzuoli; however, the unrest virtually ended in December 1984, without any eruption occurring [31].

Studies of the unrest mechanism and caldera dynamics using different physical approaches are useful to provide assessments of the volcanic risks of this highly densely populated area. The caldera of Campi Flegrei is characterized by the occurrence of a large scale hydrothermal system, at a depth of hundred meters to few kilometre of depth, whit high temperature (>100 °C) even at shallow depth. This system interacts with the magma reservoir located at a maximum depth of 8 km, which was detected by the seismic tomography experiments [46]. At shallower depth, the eventual presence or not of smaller magma batches is not yet clear. A large number of studies presented different models to explain the uplift of the caldera observed during the 1970–1972 and 1982–1984 unrest. Same of these relate the uplift to the pressure increases in a shallow magma body (3–4 km in depth) located below Pozzuoli, while other models accounts for the interaction between magma and overpressured fluids, which supplied the main contribute to the uplift [25,31,45,47–57].

Located West of Campi Flegrei caldera, the Ischia island is formed by volcanic rocks deriving from eruptive centres largely destroyed or covered by subsequent activity. The oldest outcrops date back about 150 ka BP while the most recent eruption occurred in 1301–1302 A.D. The central sector of the island is made up by Mt. Epomeo (787 m a.s.l.), a structure uplifted by the resurgence of the caldera formed after the large explosive eruption (55 ka BP) which deposited Mt. Epomeo Green Tuff (MEGT) (Fig. 7). The resurgence phase started about 33,000 years ago, producing the Mt. Epomeo structure whose edges are marked by a NW-SE and NE-SW and N–S system of faults and fractures [37,58–65]. The total average uplift of about 800 m, inferred from the present height of marine deposits on Mt. Epomeo, occurred as a discontinuous process at an average velocity of about 3 cm/year. The resurgence, generally interpreted as due to the increase in pressure of a shallow magmatic body, was accompanied by volcanic activity external to the resurgent block with dome emplacement, spatter cones and tuff rings in the eastern side. This evolution culminated with the dismantlement of its southern slope by avalanching [58,64] (Vezzoli, 1988; Tibaldi and Vezzoli, 2004), and seismicity since 1228 confined in the northern sector, while moderate volcano-tectonic processes occurred in the western slope of the island. The supposed trachytic intrusion, whose top is located at about 2 km of depth, is responsible of the active hydrothermal circulation and vigorous surface hydrothermal manifestations, with maximum temperature of the surface water of about 100 °C [65–68].

3. The Neapolitan Volcanoes in the history: volcanology and natural resources

The Neapolitan volcanic area has been the site where the Western Europe civilization was born, and continued for over 25 centuries. Cuma, at the Northern edge of Campi Flegrei, and Ischia volcanic island were the first settlements of Greek civilization in Italy, dating back the VIII century BC. During the Roman age, Vesuvius and Campi Flegrei hosted the most important towns of the Empire, for commercial and military purposes as well as luxury homes of the Roman aristocracy. Baia, west of modern Pozzuoli, hosted the largest port for Roman navy; Pompeii, close to Vesuvius, was a leading commercial port, whereas Herculaneum, located just below Vesuvius, was a rich and elegant town home to

Fig. 6. Campi Flegrei caldera. The dotted line is the limit of the caldera inferred from the Bouguer anomaly (after Scandone et al., 1991). White circles are the location of shallow wells drilled since 1939; red circles are the deep wells drilled during the AGIP-ENEL Joint Venture until 1980. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

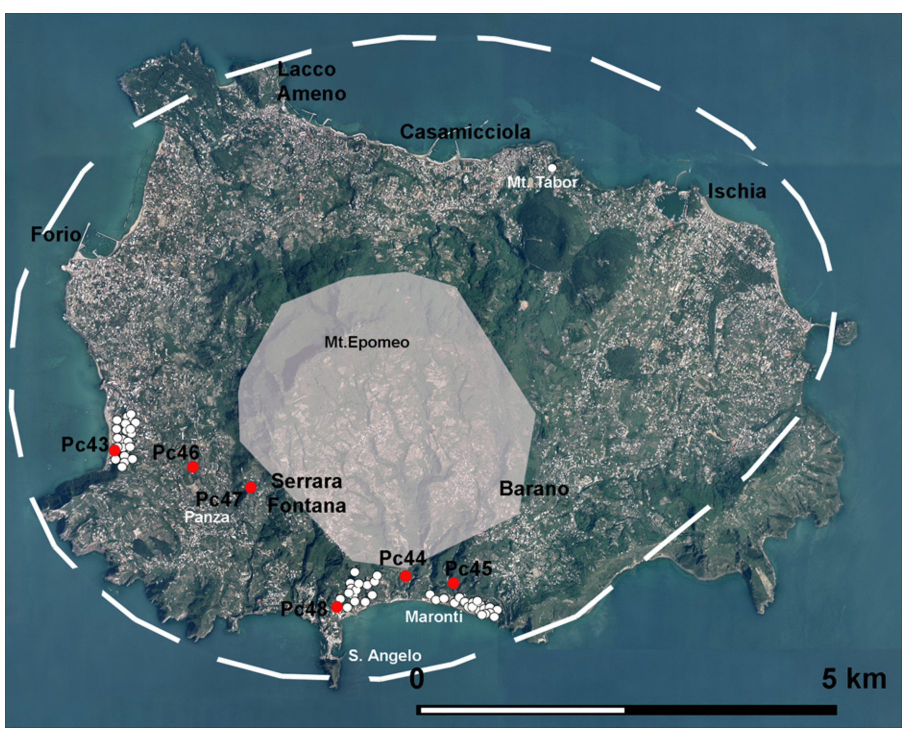

Fig. 7. The island of Ischia. The dotted line represents the caldera rim, while the shaded zone is the area which undergone to the resurgent process since at least 33 ky. White circles are the location of shallow wells drilled since 1939; red circles are the deep well drilled since 1954. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

political, military and cultural aristocracy. During the Middle Age, and the modern age until the middle of the 19th century, this area continued to represent the focus of the European culture. Most of the historical prosperity of Neapolitan area was due to its volcanic nature and geothermal resources. The fertility of the volcanic soils, the presence of thermal hot springs particularly appreciated by Romans; the variety of the landscape, marked by gentle hills looking at sea, represented by the volcanic cones of Campi Flegrei; the round and deep Gulfs, formed by volcanic collapses, protecting the fishing and the navigation; all these elements made up its fortune and appeal for so many centuries. The spectacular geothermal activity of the area, visible in fumaroles and diffused volcanic gas emissions, shot the imagination of ancient peoples, loving warm and healthy water in 'Thermae', and feeding mythological feelings, like the Averno lake where Roman poets located the Hell's gates. Modern geological and volcanological research was also born in these areas. The unrest of the Campi Flegrei caldera recorded by marine incrustations and shells over the marble columns of the Serapis temple in the ancient Roman market, attracted the attention of the most eminent scientists of the 18th century, and furnished the first proof that, in volcanic areas like that one, the ground could uplift and subside of tens of meters, with respect to the sea level. Charles Lyell (1797–1875) [69], fascinated by the proofs of impressive ground deformation testified by the columns of the Serapis temple, put them on the cover of its book 'Principles of Geology' (1830), the first text on Geology in modern sense, and a benchmark of the scientific theory of 'gradualism', who gave rise to the modern geology. A decade later, in 1841, the Bourbon Kings of Naples started to build, on the highs of Vesuvius, the first volcanic observatory in the World, aimed to apply the recent discoveries in physics and electro-magnetism to the study of volcanic eruptions: the Osservatorio Vesuviano, inaugurated in 1845 during the 7th International Conference of Scientists in Naples.

In recent time, the attention of volcanologists was drawn again in Neapolitan area, since two phases of uplift, occurred during 1970–1972 and 1982–1984, when the town of Pozzuoli, located in the centre of Campi Flegrei caldera, was raised by 1.7 m and 1.8 m, respectively. During the 1982–1984 unrest episode, more than 15,000 shallow earthquakes (in the depth range 1–5) with a maximum magnitude of 4.0 were recorded by the seismic stations of the Osservatorio Vesuviano [70], and the ground uplift occurred at an average rate of $0.3\,\mathrm{cm\,d^{-1}}$. The last episode of unrest indicated the possibility of an imminent eruption, forcing the authorities to evacuate Pozzuoli; however, the unrest virtually ended in December 1984, without any eruption occurring [31]. These episodes pushed the scientists to deepen the understanding of the Campi Flegrei caldera behavior by using physical and computer modeling [31,40,45–52,54–56,71–79].

The strong interest for the volcanism in the neapolitan area is due to the high volcanic risk for population; in particular, since the end of World War II, the intense urban development around explosive volcanoes exposes some millions of inhabitants to volcanic risk.

Due to such high volcanological and civil defence interest, in recent times several projects have been funded to understand Neapolitan volcanism and to mitigate seismic and volcanic risk. Among them, the *Progetto Finalizzato Geodinamica*, which was launched after the Irpinia earthquake occurred on November 23rd 1980 and right after the Campi Flegrei unrest of the 1982–1984. This project also provided a detailed reconstruction of volcanic activity and dynamic of Vesuvius, Campi Flegrei caldera and Ischia [14,36,58].

The advancement of scientific knowledge on these areas was also stimulated by the application of innovative exploration technologies, such as the seismic tomography. At the end of 1990s two international projects at Vesuvius (TOMOVES, see [29]) and Campi Flegrei (SERAPIS, see [14,77]) allowed the reconstruction of the shallow crust by using active seismic soundings. An important result was the detection of a low velocity zone beneath Vesuvius and Campi Flegrei caldera, in the depth range 8–10 km, which was interpreted as a widespread magmatic reservoir feeding large eruptions in the area [29,46,77]. Furthermore, the obtained results confirm the hypothesis of Moho upwelling below the Campanian volcanic district, causing the migration of magma in the shallow crust and producing an anomalous high heat flux and a diffuse shallow hydrothermal activity. These phenomena, mainly active at Campi Flegrei caldera and Ischia, encouraged, since 1930, several studies aimed to assess the geothermal potential for electric and thermal energy production.

4. Geothermal explorations in Italy and Campania

In Italy, just from the 19th century, it became clear that the heat supplied by the Earth interior represented an energy resource, an idea that was put into practice after the Industrial Revolution, for the first time at Larderello (Italy). Here, from the early 20th century, a number of wells were drilled for the exploitation of thermal energy, and later, when the drilling techniques were improved, the exploitation was extended to the whole geothermal area. In 1904, the Prince Piero-Conti Ginori, performed few experiments aimed to transform the thermodynamic energy of the vapor into electric energy, by using a 1 Hp motor matched with a dynamo, which lighted few bulbs. This experience lead to the growth of geothermal explorations in Italy, as an alternative to the conventional oil industry, which involved, at the early 1930s, the active volcanic areas of Ischia, Campi Flegrei and Vesuvius. Starting from the end of World War II, a relevant technological development in many applied fields (i.e. telecommunications, transports, mining, geophysics, etc.) was taking place. Such a development in turns reflected into an increased amount and quality of data on earths phenomena, giving a strong pulse and support to Earth science studies. Geophysical surveys using sophisticated sensors allowed to recognize the density and the rheology of the shallow crust down to few kilometers of depth. Moreover, the results obtained by oil exploration were used for the geodynamical interpretation of the Italian peninsula. The geological studies developed in Italy until the 20th century, and particularly those related to the volcanism, characterized by high heat flux (Fig. 3) as a consequence of spreading of the Tyrrhenian basin occurring since 2 My ago [3,7]. This area is characterized by the presence of NW–SE volcanic alignments which are grouped in different co-magmatic province of Tuscany, Latium and Campania. The attention to the geothermal exploration was also stimulated by the increase of energy demand and by the 1973 oil crises, which culminated with the oil supply interruption provided by the OPEC (Organization of the Petroleum Exporting Countries).

In the Campania region the presence of hot water and fumaroles was just well known, since the 16th century, due to the spa use. At Ischia, from the mid 16th century, Giulio Iasolino (1538–1622) [80], a doctor from Calabria, professor of anatomy at Naples University, started a systematic study of the hot springs on the island, which he introduced into curative practice. This culminated in 1588 with the publication of "*De' rimedi naturali che sono nell'isola di Pithecusa, hoggi detta Ischia*" (On the natural remedies on the island of Pithecusa, today called Ischia) [80], a work of great importance and editorial success, which was to boost Ischia's fame, thanks in part to the useful map of sites included, engraved by the mapmaker Mario Cartaro from Viterbo, which was later used in the most important European atlases. Interest in Ischia also grown due to the eruption of the nearby Campi Flegrei in 1538 A.D., which made the more popular thermal baths of Pozzuoli

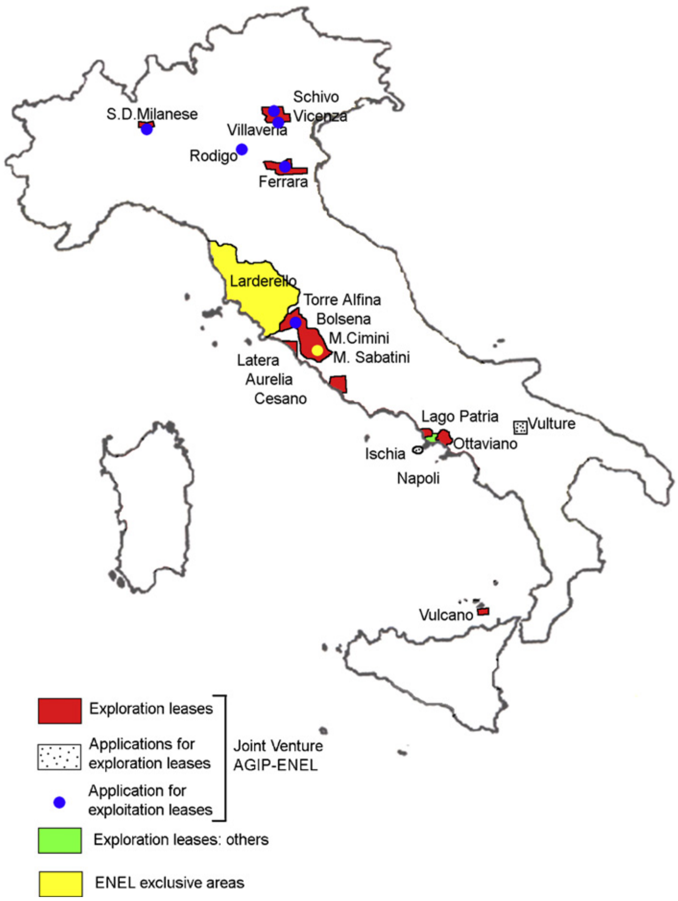

Fig. 8. Exploration leases if Italy since 1977.
From AGIP (1987).

and Baia impracticable ([1] and reference therein). The interest for the extensive geothermal fields at Ischia and Campi Flegrei, turns from a merely spa use to a geothermal exploitation during the XX century. The site location of many drillings, particularly at Ischia, was chosen very close to the shoreline, since the sea water was used for cooling the working fluid (C_2H_5Cl) [81]. The first main drillings investigation was performed at Ischia and Campi Flegrei, from 1939 to 1943, by the SAFEN Company. The geothermal surface manifestations of these areas (hot springs and fumaroles), with temperature of about 100 °C, suggested the presence of a high geothermal potential in the shallow crust [81]. The researches continued later, in the framework of the Joint Venture AGIP-ENEL companies, and were focused in the Campi Flegrei area, starting from 1979. Several wells reached few kilometers of depth, with a maximum depth of 3 km [3]. The geothermal researches interested also the Vesuvius area, starting from 1952, after the 462 km^2 "Ottaviano" exploration licence issued [3]. The aim was to test under which conditions high enthalpy fluids (>150 °C) could be commercially produced from reservoirs related to active central volcanoes [82]. Thus, a 2072 m well depth was drilled, from 1980 to 1981, in the south-east sector of the Vesuvius (Trecase well).

In the middle of 1980, thanks to the results obtained by various researches, which involved different areas of Italy, a reliable picture of the geothermal potential for thermal and electric uses was obtained. The exploration licences, at that time, interested a global area of 8200 km^2 (Fig. 8), about 2% of the total surface of Italy. In December 1983, the installed geothermal power was about 456 MW, while the Italian Energy National Plan forecasted an increment of the power of further 200 MW during the incoming years [2]. A complete report of the geothermal exploration state of art was presented during the "Workshop for the Exploitation of Geothermal Energy for Production of Electric and Thermal Power" held in Florence in 1984. In the framework of ENEL and AGIP activities, the report identified the most interesting regions of Italy for geothermal exploitation in the range of both low and high enthalpy; in contrast, at the moment only the Tuscany region is the site of productive geothermal power plants [2]. The main identified geothermal areas are the following:

- Tuscany (Larderello, Travale-Radicondoli), with temperature up to 400 °C at 3 km of depth;
- Mount Amiata (Tuscany), with temperature up to 350 °C at 3.5 km of depth;
- Torre Alfina (Latium), with temperature up to 150 °C at 2.2 km of depth;
- Cesano (Latium), with temperature up to 150 °C at depth of about 1 km;
- Latera (Latium), with temperature up to 170 °C at 2.6 km of depth;
- Sabatini Mounts (Latium), with temperature up to 290 °C at 2.5 km of depth;
- Lago Patria (Campi Flegrei, Campania), with temperature up to 420 °C at 3 km of depth;
- Vulcano (Sicily), with temperatures in excess of 400 °C at very shallow depths;
- San Donato Milanese (Po Valley), with temperature up to 62 °C at 2.2 km of depth;
- Ferrara (Po Valley), with temperature of 100 °C at 1.3 km of depth.

The above results show that the Campania region is the area characterized by higher temperatures at shallow depth, which are useful for the exploitation of geothermal energy in the high enthalpy domain. Also at Ischia, the results of SAFEN drillings, showed the occurrence of high temperature (200 °C) at depth of few hundreds of meters [3]. On the other side, the temperature gradient measured within the Trecase well at Vesuvius, was lower then expected (about 30 °C km^{-1}), although the rather periferical location of drilling could have missed the geothermal system, which from indirect considerations would be much more concentrated below the crater area [83]. The data obtained after the explorations in Campania also allowed a better knowledge of the volcanic processes occurred at Ischia, Vesuvius and Campi Flegrei caldera. These data have been collected in various technical reports of AGIP and scientific publications representing, nowadays, an important database for geological, geochemical, volcanological and petrological studies [3,81,82,84–93]. The increase of geothermal energy production in Italy, as forecasted by the Italian Energy National Plan, was not followed, and, except for Tuscany region, the project of geothermal exploitation was abandoned at the end of 1980 years. Nowadays, the geothermal energy in the world is harnessed on a large scale for space heating, industry and electricity generation. The geothermal electrical installed capacity in the World was 7974 MWe (year 2000) and the electrical energy generated was 49.3 billion kWhy^{-1}, representing 0.3% of the world total electrical energy. In Italy the geothermal electrical installed capacity (year 2005) is about 800 MWe, with energy production of about 5.6 GWh per year, which represents 1.7% of national needings, while for direct uses the capacity is about 300 MWt [94,95] In recent time, the interest for geothermal exploitation in Campania region was raised by many converging reasons. The strongest pulse towards such a new interest was due to the "Campi Flegrei Deep Drilling Project" (www.icdp-online.org), which raised growing interest not only in deep volcanological research but also in the geothermal exploration and exploitation. In the following sections, we describe in detail the main results obtained during the 50 years of geothermal exploration of Campanian volcanic districts (Campi Flegrei caldera, Ischia and Vesuvius) and obtain estimates

of geothermal potential for industrial use. In particular, we refer to the research leases of "Lago Patria" (Campi Flegrei caldera and Ischia) and "Ottaviano" (Vesuvius) and to the drillings performed by the SAFEN and AGIP Companies and the related data obtained during the pumping tests [3].

5. Campi Flegrei

The first geothermal explorations in Campi Flegrei (Lago Patria lease) were carried out by the SAFEN Company during 1939 and 1943, which drilled 19 wells (id: LA, CLV, CMV, A) with depth from few meters to 600 m [81,84] (Table 1 and Fig. 9a and b). The investigated area was characterized by a vigorous fumaroles fields, named with the local appellative of "mofete". The drillings showed the potentiality of this area (Mofete area), with the presence of a water dominated system at temperature of about 200 °C and relative high pressure (Fig. 10). The methods and the technology adopted during that time, did not allow the complete defining of physical and chemical properties of geothermal fluids [85]. These fluids have an elevated salinity which caused problems during their withdrawal. For instance, within the CLV7 well, which produced a maximum water and vapor flow rate of $40 th^{-1}$, the persistence of minerals precipitation generated a self-sealing phenomenon with a consequent decreasing of flow and productivity of the well. Nevertheless, the CLV7 and CLV17 wells were initially productive, with a flow rate of about $7 l s^{-1}$ and temperature of water-vapor mixture, at well head, of about 100 °C. Furthermore, the temperature measured in the wells showed a radial decreasing from the centre of the caldera. The mid term productive tests (4 months) also demonstrate that the superficial water level in the wells did not varied significantly during the fluid withdraw. In the early 1940, a new well was drilled within the crater of Monte Nuovo (CMV well) (Fig. 11). This was the result of the last volcanic activity (1538 A.D.) occurred in Campi Flegrei, for this reason the experts considered that a sufficient amount of heat, for high temperature vapor production, was still contained in the shallow magmatic reservoir which fed the eruption [84,96]. The drilling, lasted about 5 months by using a direct push rig, reaching a depth of 667 m and a maximum temperature of 78 °C, lower that that expected. This was due to the cooled investigated pyroclastic deposits, originated by the Mt. Nuovo phreatic eruption. At the time of this drilling, the knowledge of volcanic processes was not clear. At the present, it is well know that monogenic volcanoes are supplied by dikes, which cool rapidly after their emplacement. A further shallow drillings field was carried out in 1940, at Agnano (A1, A3, A6 wells), at a distance of 1.5 km from the Solfatara crater. Also in this case, the results of the drillings were not satisfactory and the exploration of this area was temporarily stopped, when a depth of about 100 m was reached and a temperature of 30 °C [84]. The geothermal exploration of the whole Campania Plain, was also suspended for the World War II occurrence, in September 1943. Later, from 1953 and 1954, a new drilling (CF23) was performed at Agnano (Fig. 6), with a depth of 1840 m and a maximum temperature of about 300 °C at the bottom. The high temperatures recorded at shallow depth, in particular in Mofete area, stimulated further interest in the geothermal research, calling for a new regional drilling program carried out, since 1977, by the established AGIP-ENEL joint-venture, which ended in 1985. Such a program was decided by the Ministry of Industry (AGIP and ENEL were at the time State companies) in search for alternative energies because of the large peak of oil price due to the 1973, Israelo-Arab war. The aim was both to test the exploitation of high temperature fluids using an extraction/reinjection system and to monitor the perturbation of the deep geothermal system (pressure, water level and capacity) induced by the presence of active wells. Because of the substantial depth of the wells and their closeness to highly urbanized area, particular care was paid to the protection of the environment. Many surveys of micro-seismicity, deformation, soil gas emission were carried out before, during and after the drillings [85]. The researches were extended to the neighboring area of S. Vito, to the north of Pozzuoli, and to Licola (L1 well) located outside the north-west caldera rim. The latter was planned to evaluate the area extension of the thermal anomaly observed at Mofete (Fig. 6). In Mofete area, 7 wells (4 deviated and 3 vertical) were drilled (MF 1, 2, 3d, 5, 7d, 8d, 9d) with depth ranges from 800 to 2700 m. The deviation allowed to intercept the possible fractures and faults zones from which to obtain a better production, avoiding the extension of the wells field close to the urbanized areas [89]. At the end of 1985, the results of the drillings defined the following picture:

no. 4 productive wells (1, 2, 7d, 8d);
no. 2 injection wells (3d, 9d);
no. 1 unproductive well (5).

The results at Mofete identified three main aquifers localized within the tuffs and volcano-sedimentary formations, at a depth of 500–1000 m, 1800–2000 m, 2500–2700 m, respectively. Only the two shallower layers were productive for geothermal exploitation, showing maximum temperatures between 250 and 300 °C. The wells are characterize by a vapor–water mixture with a well head temperature of 180 °C–230 °C, TDS of $30–70 g l^{-1}$, 20% in weight of non condensable gases. The flow rate of the shallower aquifer was $200 th^{-1}$ with maximum pressure of 0.8 MPa (8 bar). The intermediate aquifer was characterized by a lower flow rate of $70 th^{-1}$ but an higher content in weight of vapor (40%), thus the resulting enthalpy was $1100 kJ kg^{-1}$ for the shallower aquifer and $1600 kJ kg^{-1}$ for the intermediate one. The characteristics of the wells and productive reservoirs were established through both short (2–3 days) and long (3–4 months) pumping tests [89]. In the former case the fluids were collected into settling tanks, while in the latter case the fluids were re-injected into a well that was also utilized to study the behavior of the geothermal system. At the end of the investigations was established a potential production of Mofete wells of about 10 MW.

Also from the geochemical point of view, the Mofete geothermal field indicates a multiple reservoirs. The geochemical survey indicates that the thermal waters are a mixing of local meteoric waters and deep hot waters of marine origin with indications of local leakage of steam [97]. In particular the MF 1 indicate the presence of a water dominated reservoir at 500–900 m in fractured volcanics with large quantities of saline water (43,000 ppm TDS, corresponding to 30,000 ppm TDS at reservoir conditions) with a temperature of 247 °C. Uncommercial quantities of fluids (65,000 ppm TDS at surface corresponding 395,000 in the reservoir) were produced from below 1223 m.

The MF 2 has encountered in fractured volcano-sedimentary rocks (1300–1900 m depth) saline fluids (380,000 ppm TDS, corresponding to 18,200 ppm at reservoir conditions) with a temperature of 337 °C.

The MF5 produced for a short time from 2700 m very hyper saline fluids (over 500,000 ppm TDS about 150,000 ppm in the reservoir) at a bottom hole temperature of 347 °C.

The MF 3d, 7d, 8d and 9d tapped the Mofete 1 reservoir between 500 and 1500 m vertical depth with a bottom temperature of 230–308 °C and a salinity of 40,000–75,000 pmm TDS at atmospheric conditions, corresponding to 28,000–52,000 ppm in the reservoir.

Chemical composition of the brine was measured at atmospheric pressure and is given in Table 2 and 3 ad ppm. From the above values is possible to do some simple considerations concerning the fluid circulation of Mofete field. The chemical data of

Table 1
Synthesis of drilling at Campi Flegrei performed from the 1939 to 1943 (Penta e Conforto, 1951). The drilled lithotype are: (a) Trachitic Tuffs and unwelded pumices, (b) Yellow Tuff; (b') Grenish Tuff containing small white pumices and lithics, (c) Gray Tuff sometime lithified with layered lavas.

Well	Head well elevation (m a.s.l.)	Depth (m)	Water table (m a.s.l.)	Encountered soils (formation type)	Maximum temperature (°C)	Data of drilling	Surface temperature (°C)	pH	Other technical description
LA 1	35.5	72.7	1.49–2.3	0–14 m: type a; 14–72.7: type b'	111	March–April 1939	100–108	6.28–10	
LA 2	23.7	93	0–1.5	0–16 m: type a; 16–86.4: type b'	104	August–September 1939		6.7–6.9	Rotary drilling
LA 3	6.32	95.65	0–0.6	0–17 m: type a; 17–95.7: type b'	69	May 1939	69		Rotary drilling
CLV 7	52.9	585.5	5.9–52	0–12.5 m: type a; 12.5–115: type b'; 115–518: type c	225	1939–1942		6.5–7.8	Casing up to 542.9 m from well head. Well eruption occurred on the 7th April 1941 with water emission up to the 5th August 1942
LA 8	30.29	43.2	0.29–0.30	0–5.7 m: type a; 5.7–40.1: type b; 40.1–43.2: b'	49	28th November–12 December 1940	42–49	6–6.5	Wire drilling
LA 9	38.96	49.5	0.04–0.3	0–7.2 m: type a; 7.2–49.5. type b	44	19–30 December 1940	32–40	7.5–8	
LA 10	12.49	22.5	0.3–0.8	0–22 m: type b	85	7–29 January 1941	78–83	7–7.35	Wire drilling. Casing up to 21.30 m from well head.
LA 11	72.5	80.8	0.7–1.4	0–44 m: type a; 44–80.8. type b'	107	7–29 January 1941	100–105	7–9	Casing up to 80 m from well head.
LA 12	76.7	84.5	3.2–3.7	0–44 m: type a 44–80.8. type b'	102	7–21 February 1941	95–100	7.6–8	Casing up to 82 m from well head
LA 13	57.37	92.4	1.3–2.37	0–53 m: type a; 53–92.4. type b'	75	1 March –24 April 1941	70–73	7–8	
LA 14	79.82	92.4	−1.4 to (−1.27)	0–82 m: type a; 82–92.4. type b'	105	11–28 June 1941	90–100	7.4–7.5	
LA 15	83.59	90.0	0.4–0.9	0–32 m: type a; 32–64: sends 64–90: type b'	107	5–22 September 1941	101–106	7–8	
CLV 16	64.10	400.0	0–4	0–40 m: type a; 40–146: type b'; 64–90: type b'	135	22 July 1942–1 April 1943	100		Casing up to 187.5 m from well head
CLV 17	80.89	521.7	−7.5 to 6.0	0–51 m: type a; 51–145: type b'; 145–340: type c; 340–426: altered tuff; 426–521.7: type c	224	5 August 1942–24 April 1943	85		Wire drilling. Casing up to 357 m from well head. Well eruption occurred on the 3rd July 1943 with vapor emission mixed with tuff material from the wall well lasted few days.
CLV 20	39.7	252.5	0	0–17 m: type a; 17–38: type b; 38–121: type b'; 121–217: type c; 217–252.2: altered tuff	85	April 1943 and interrupted on the 9th September due to the War World II	45		
CMV	13	676.9	−2.8 to 0	Lava scoria and pumice	78	January 10th –June 2nd 1942	60	7.2	
A 1	17	107.7	n.a.	Altered tuff	30	January 1940	18 @ 4.25 m		Rotary drilling. Casing up to 100 m from well head
A 3	n.a.	19.65	n.a.	Altered tuff and send	19	December 1941	19 @ 3.5 m		
A 6	25	24.85	n.a.	Altered tuff	21	February 1941	21 @ 16.6 m		

After Penta e Conforto (1951).

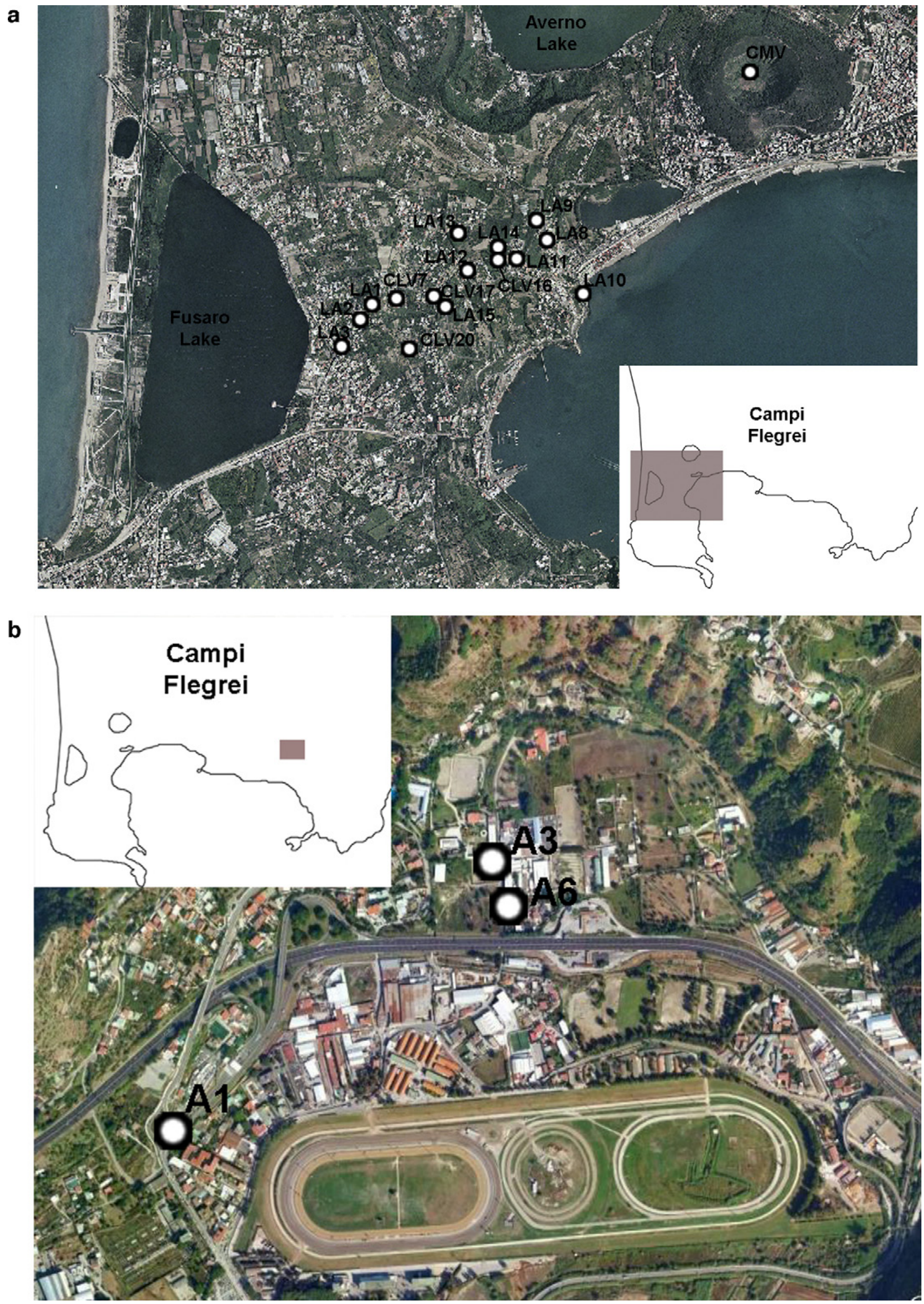

Fig. 9. (a) Shallow wells (down to about 600 m) of Mofete geothermal area (LA, CLV) and Monte Nuovo (CMV). (b) Shallow wells (A) of Agnano geothermal area.

the shallow reservoir for the MF1, MF3d, MF7d and MF9d are very similar at the same depth. An increase of salinity (i.e. higher Na/Li and Cl/B) is shown in MF1 and MF3D with the depth. Such increase can be due to the higher formation temperatures, which rise with depth from 230 to 308 °C. The similar Na/Cl of the MF1 and MF2 at the same depth points to a common origin of the brines. However the much lower salinity of MF2 intermediate reservoir at a short distance from the MF1 well can be explained by considering the two reservoirs separated. The deep reservoir from MF5 shows a completely different geochemical composition for the shallow and intermediate reservoirs (Table 3).

A possible model of how the Mofete field originated, taking into account the above discussed fluid chemistry and other elements, can be envisaged as follow: in a first deep reservoir (i.e. MF5) the original sea water brine was concentrated to the present values because of evaporation due to the effect of the high temperature and limited recharge; consequently there was a loss o steam which migrated to the upper reservoirs. During its ascent the

Table 2
Chemistry of water separated at atmospheric pressure (ppm).

	Shallow reservoir						Intermediate reservoir	Deep reservoir
	MF1 (550–896 m)	MF1 (1273–1506 m)	MF3D (430–665 m)	MF7D (1110–1648 m)	MF3D (552–907)	MF9D (1339–1749 m)	MF2 (1275–1989 m)	MF5 (2310–2599 m)
Na	14320	20860	13790	14750	14590	21300	10600	85160
K	1760	3880	1122	2510	1526	4410	2467	43380
Ca	792	2124	714	790	752	3520	1005	53950
B	178	183	106	1440	90	288	295	231
Sr	49	58	43	26	41	54	30	1310
As	13	17	15	26	15	32	22	
Li	36	46	34	56	37	56	28	480
Mn	10	28	4	10	8	55	52	5510
Fe	1	3	3	21	1	2	1	9450
SiO_2	568	590	425	639	454	578	938	210
Cl	25304	37800	23393	25650	25171	43897	21169	313850
HCO_3	116	77	110	195	98	73	85	Traces
SO_4	72	7	156	70	82	14	12	Traces
TDS	42860	55509	39428	45997	42965	75695	37880	515902
Na/Li	398	453	406	264	394	380	379	177
Cl/B	142	207	221	185	280	152	72	1359
Na/Cl	0.57	0.55	0.59	0.55	0.58	0.49	0.50	0.27
ph	7.5	5.5	7.5	7.2	7.7	6.9	6	4.5

From Carella and Guglielminetti (1987).

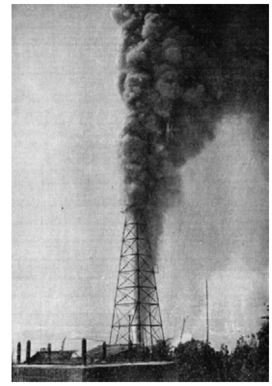

Fig. 10. 1st July 1943 well eruption at Mofete with formation of a geyser. From Penta (1949).

Fig. 11. The Mt. Nuovo crater formed during the last eruption of Campi Flegrei in 1538.

steam entered into the MF2 intermediate reservoir and, condensing because of lower temperatures, caused a consistent dilution of the MF2 brine which again one must suppose poorly connected with the seawater recharge zone. A very minor quantity of steam remained to alter only marginally the upper reservoir (MF1, MF3d,

Table 3
Water chemistry for selected samples calculated at reservoir condition (ppm) (from Carella and Guglielminetti, 1987).

	Shallow reservoir		Intermediate reservoir
	MF1 (550–896 m)	MF1 (1273–1506 m)	MF2 (1275–1989 m)
Na	10025	12589	5090
K	1230	2342	1180
Ca	555	1281	480
B	125	110	140
Sr	34	41	14
As	9	11	11
Li	25	28	13
Mn	7	17	25
Fe	1	2	1
SiO_2	398	417	450
Cl	17710	22310	10200
HCO_3	81	46	41
SO_4	50	4	5
TDS	30000	39500	18200
Na/Li	398	453	391
Cl/B	142	207	73
Na/Cl	0.57	0.55	0.50

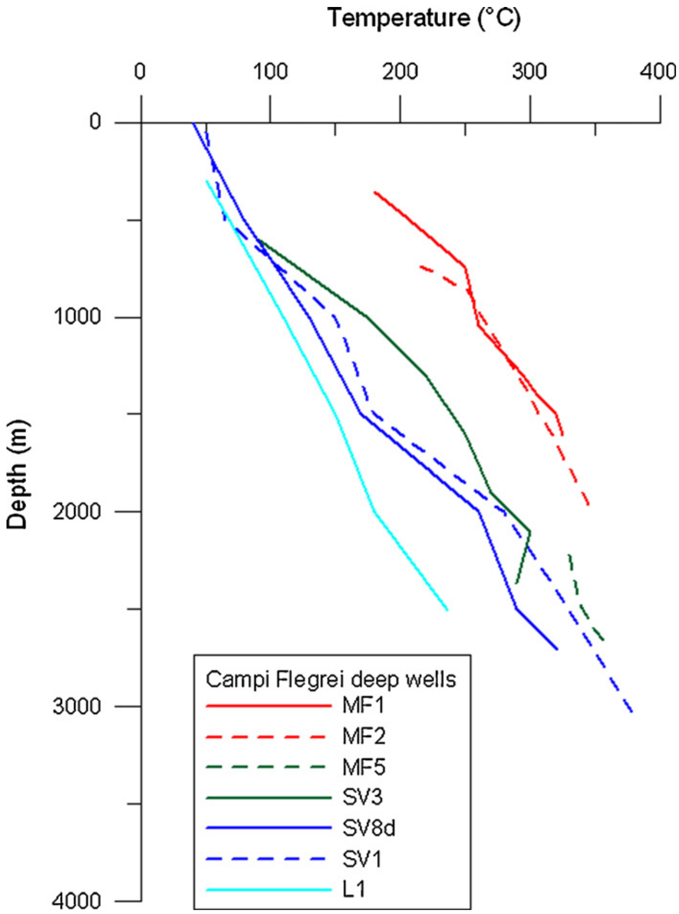

Fig. 12. Temperature profiles measured during the drilling of the deepest wells at Campi Flegrei.
After AGIP (1987).

MF7d, MF8d and MF9d) better connected with the sea, and to escape at the surface.

In December 1979, a new drilling program was started in S. Vito area, few kilometers north of Pozzuoli town, with 3 wells (SV1, SV8d, SV3) (Fig. 6) of maximum depth and temperature of 3046 m and 420 °C, respectively. During the production tests a temperature of 220 °C and pressure of 70 kg cm^{-2} were measured at wells head. The SV1 well crossed the caldera rim whose collapse was estimated of about 600–700 m on the basis of stratigraphic correlations between the outcropping Yellow Tuff close to the Gauro crater and its depth in the well. The highest temperatures (about 400 °C) were measured by using a zinc alloy with melt temperature of 419 °C. Before starting the measure, the drilling operations were stopped for some time, to let the temperature of the system stabilize [88]. In order to evaluate the extension of the thermal anomaly of the investigated area a new drilling was carried out at Licola (L1), located outside the caldera rim, close to Cuma north of the caldera. This choice was also helpful for the reconstruction of the stratigraphic sequence which was not affected by volcano-tectonics events due to caldera formation. The recorded temperature in the L1 well was substantial lower than those measured in S. Vito zone, highlighting that the thermal anomaly is confined within the caldera rim [98] (Fig. 12).

6. Ischia

The geothermal resource of Ischia Island was well known since the 16th century and was utilized just for thermal baths and wellness [80]. At the end of 20th century more than 180 spa and 130 thermal pools, fed by 200 wells, were operative in the island [92]. This spa activity nowadays represents the main economic resource of Ischia, while the planned exploitation of the huge geothermal resource for industrial uses has been not accomplished yet. Only minor use of this resource is related to low enthalpy applications for buildings heating. The first geothermal exploration of the island was operated since 1939–1943, in the western and southern sectors, Cetara (Forio) and Maronti (Serrara Fontana) and in the northern sector Mt Tabor (Casamicciola). Such exploration consisted of 84 drillings, only 3 of which reached more than 100 m of depth. Few of these wells were used for irrigation and are not reported here, since they did not provide useful data. From 1951 to 1954 the SAFEN Company carried out further 6 drillings, 3 of which reached a depth of more than 500 m. Thus a total of 90 drillings were performed at the end of 1954 [84] (Figs. 7 and 13a–c). Some of the wells were utilized to check the water table changes during pumping tests. The drillings were temporarily stopped during 1943, due to the war events. The wells were drilled in the western and southern sectors of the island, where the most vigorous fumaroles and geothermal manifestations are localized. In these areas the surface temperatures can reach about 100 °C [3]. In the eastern sector of S. Angelo peninsula 20 drillings (I,S,IFV) were performed (Table 4) (Fig. 13a), only 3 are deeper than 100 m. The drilling operations lasted from 1939 to 1943; during this period, despite the continuous hot fluids withdrawal, there was not a reduction of geothermal manifestations and temperature at the surface [84]. The geological information provided by these wells was not very significant, since they involved just the surface formations of reworked tuffs and volcanic breccia. In the 1939 second half-year, 22 wells were drilled in the southern sector of the island (Maronti) (Fig. 13b), with maximum depth of few tens of meters. Six wells (IM), with diameter of 310 mm, were utilized for the pumping tests, 13 (T) wells, with diameter of 245 mm, were exploited as monitoring-wells and 3 (which are not reported here) were utilized for irrigation (Table 5). The measures of the water table highlighted its regular oscillation related to water flow seasonal variations, while the increase of water level was generally accompanied by a decreasing of temperature. This evidence was ascribed to the shallowness of the wells, where the water table is rapidly mixed with the meteoric one. In the same period the researches were extended to the western sector of the island, where several fumaroles and hot springs are located, with maximum surface temperature of about 100 °C. At Forio 19 wells (ICA) for the pumping tests were drilled (ϕ = 300 mm) and 5 (S) were utilized as monitoring-wells (ϕ = 245 mm) (Table 6 and Fig. 13c). A number of the deeper wells crossed the Mt. Epomeo Green Tuff formation, whose collapse confirmed the presence of a volcano-tectonic fault with vertical slip of about 90 m [84]. This observation supported the studies of Rittmann (1930) [99], which defined the structure of Mt. Epomeo as a volcano-tectonic horst. The first phase of exploration was completed in August 1943, with the drilling of a shallow well at Casamiciola (Mt. Tabor) in the northern sector of the island. The drilling was located few hundreds meters above sea level, in order to estimate the influence of the sea on the water table trend. In this well the water table was located at the sea level with temperature of 100 °C [84]. In this case the presence of hot water can be related to the hydrothermal circulation through a N–S faults system which fed the most recent volcanic activity of the island (last 10 ka) [58]. The geothermal system of Ischia is also characterized by pressure fluctuations, which were evidenced by several wells eruptions and geyser formation occurred during the drilling, and also in recent time, after the wells closure (Fig. 14a and b). The high potentiality of the geothermal resource of Ischia, pushed the SAFEN Company to continue the exploration drilling, from 1951 to 1954, furthers wells (Pc) with maximum depth of about 1 km

Table 4
Synthesis of drilling at Ischia performed from the 1939 to 1943 at Fumaroles site (southern island sector) (Penta and Conforto, 1951). The drilled lithotype are: (a) Unwelded Tuff with greenish lithics, (b) Lavas volcanic breccias with tuffs matrix greenish-gray with, (c) Gray Tuff sometime greenish with layered lavas. (after Penta e Conforto, 1951).

Well	Head well elevation (m a.s.l.)	Depth (m)	Water table (m a.s.l.)	Encountered soils (formation type)	Maximum temperature (°C)	Data of drilling	Surface temperature (°C)	pH	Other technical description
I1	1.5	37.35	0.5	0–2 m: sabbia 2-37.35: type a	142	June 1939	73	6.6–7.4	Rotary drilling. Persistent geyser activity
I2	5.2	83.75	−1 to 4.2	0–22.5 m: type a; 22.5–83.75: type b	160	Started on 21st August 1939	90–101	6.1–7.5	Rotary drilling.
I3	12.52	14.30	2–3	0–14.3 m: type a	106	November 1939	95–100	6.2–7.1	Rotary drilling.
I4	23.2	14.80	15.2–16.8	0–14.80 m: type a	103	January 1940	102 @ 15 m	6.7–7.2	Rotary drilling.
I5	29.5	20.80	0.4	0–20.80 m: type a	103	January 1940	70	6.4–7.5	
I6	7	29.00	0.4	0–29.00 m: type a	120	July 1940	99		Wire drilling. Well eruption occurred on August 18th 1940. Successively closed and abandoned
I7	6.9	37.95	−3 to 2.3	0–30.00 m: type a; 30.00–37.95: type b	135	October 1940	77	7	
I8	7.9	80.00	1.45	0–30 m: type a; 30–70: type b; 70–80. type c	153	19 October 1940–24 January 1941	91	6	February 3rd to 16th March 1941 persistent geyser activity characterized by 11 well eruption and spontaneous production from June to September 1943
I9	22.8	24.30	0.53	0–24.30 m: type a	100	March 1941			Wire drilling
I10	30	16.5	7.5–9	0–30 m: type a	90	February 1941	81 @ 8 m	7	Wire drilling
I10A	–	17.00	–	0–17 m: type a	105	May 1941	89–100 @10 m.	7	Wire drilling
I11	40.0	45.0	32–34	0–45: type a	110	March 1941	99 @10 m.	7	Casing up to 16 m from well head
I12 not localized	–	17	–	0–17: type a	71	April 1941	40 @ 4.7 m.	7	Wire drilling. Casing up to 16 m from well head
I12A not localized	–	20	0	0–20: type a	55	April 1941	70–80		Wire drilling. Casing up to 19 m from well head
I13 not localized	–	20	0	0–20: type a	55	April 1941	22–32		Wire drilling. Casing up to 19 m from well head
S1	3.13	3.15	0.33	0–3.15: type a	67	January 1939			Inspection well
S2	5.15	4.15	1.5–3.5	0–4.15: type a	100	April 1940		6.5–7	Inspection well
IFV1	11.08	283.4	–	0–26.40 m: reworked tuff (green); 26.40–69.30: volcanic breccias and reworked tuff; 69.30–93: gray and green tuff; 93–110: altered tuff with breccia 110–263.4:type c; 263.4–283.4: green tuff with breccia	175	June–December 1941		6.5–7	Casing up to 241 m from well head. Spontaneous well eruption from February 2nd to end of September 1942
IFV2	24.6	330.0	2.6–3.6	0–23 m: unconsolidated tuff 23–78: volcanic breccia; 78–94: gray-green tuff; 94–132: altered tuff with breccia; 132–330:type c	159	April 22nd 1942–20th January 1943		7.2	Casing up to 153,3 m from well head.
IFV4	25.5	140.0	–	–	–	Started on July 3rd interupted on September 1943			

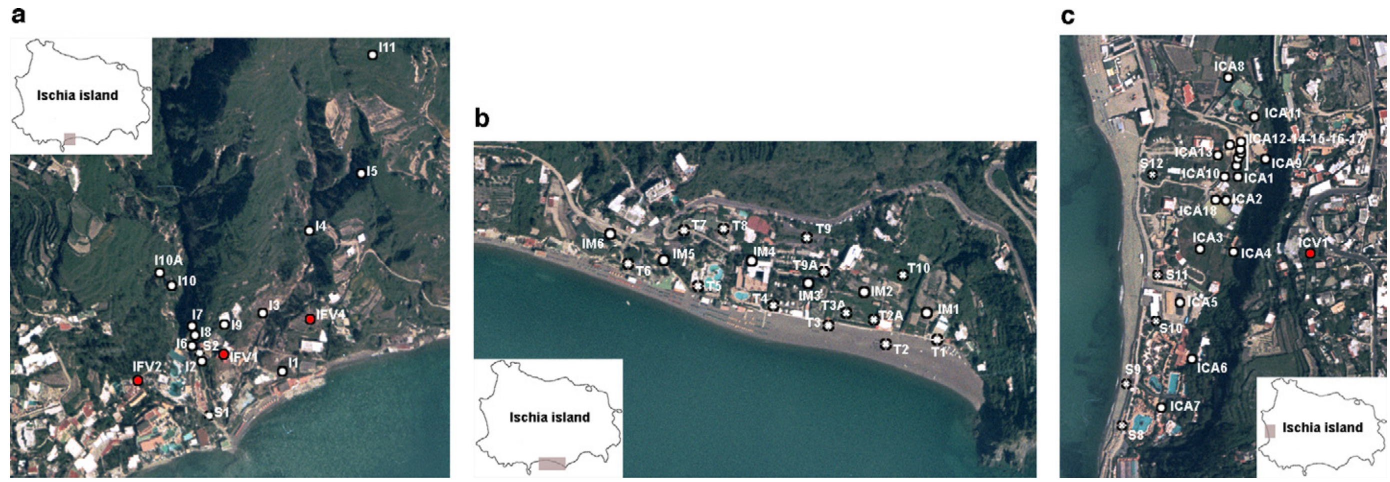

Fig. 13. (a) Location of shallow wells close to S. Angelo peninsula (Ischia). Red circles >100 m of depth, white circles <100 m of depth. (b) Location of shallow wells at Maronti (Ischia). Dotted circles are the monitoring wells used to measure the variation of the water table during the pumping tests. (c) Location of shallow wells at Cetara, Forio (Ischia). Dotted circles are the monitoring wells used to measure the variation of the water table during the pumping tests. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

(ENEL, 1987) (Fig. 7). Such drillings allowed a detailed reconstruction of the geothermal gradient at depth to better constrain the geothermal reservoir. Within the Pc46 well (Forio) were measured the highest temperatures (225 °C at 1151 m of depth) (Fig. 15). The data obtained by the SAFEN researchers highlighted that a large amount of potential resource is related to vapor dominated systems and that the useful temperatures for electric production can be generally found just few meters below the sea level [100]. In 1950, an attempt of exploitation of the geothermal resource was developed, with the installation of a 300 kW binary cycle plant. The endeavor was abandoned later, due to practical problems related to the wells corrosion, which the adopted antiquated technology was not able to solve. In more recent time, in the framework of “Progetto Finalizzato Geodinamica” a pilot plant of 500 kW, which utilized fluids at temperature of 150 °C, was planned in the island of Ischia. In this case, the failure of the project can be assigned to the lack of interest showed by the local communities, concerned by a hypothetical negative effect that the presence of a geothermal plant in the island could have on the tourism economy [101].

7. Vesuvius

The attention to the geothermal resource of Campania volcanoes was focused on Vesuvius during 1980, since experts thought that the last recent eruption of the volcano, occurred in 1944, was fed by a still hot shallow magma chamber, capable of producing an intense heat flow. The Trecase 1, in the eastern sector of volcano well, was drilled to a depth of 2.072 m, since 19 November 1980–13 March 1981 (Fig. 5). During the drilling five bottom cores were sampled by using Christiensen 6 3/4″ core barrels. The well was later closed with two cement plugs, the first from 2003 m to 1800 m and the second from 1156 m to 890 m. The encountered stratigraphy was

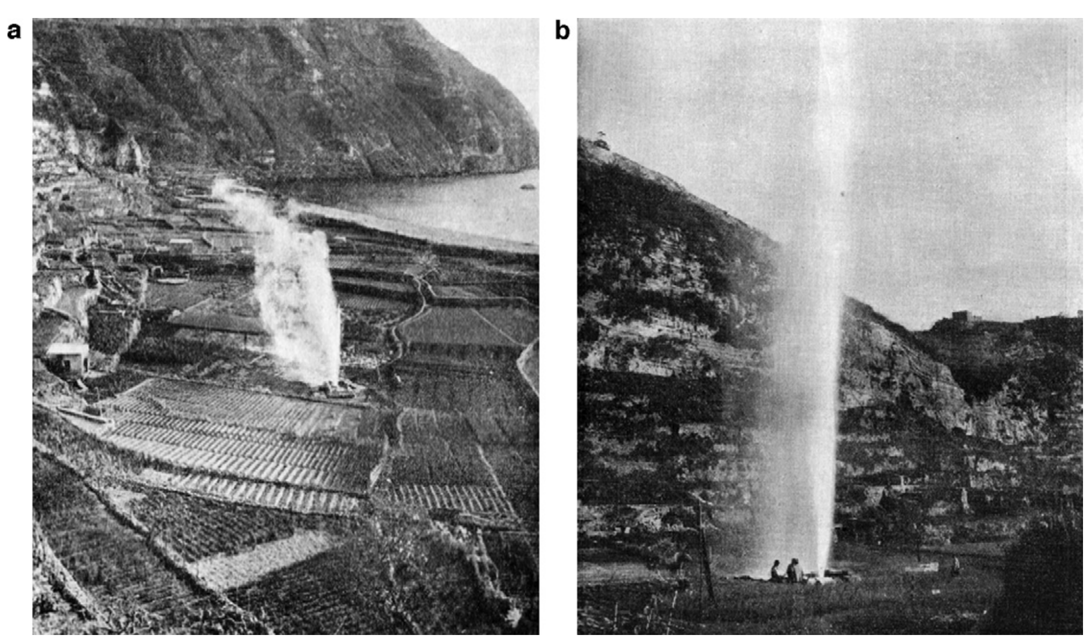

Fig. 14. (a and b) 8 April 1940 well eruption at Cetara (a) with formation of a geyser lasted 13 h; (b) 4 August 1939 eruption at Fumarole, lasted with intermittence for about 4 years.
From Penta (1949).

Table 5
Synthesis of drilling at Ischia performed from the 1939 to 1943 at Maronti site (southern island sector).

Well	Head well elevation (m a.s.l.)	Depth (m)	Water table (m a.s.l.)	Encountered soils (formation type)	Maximum temperature (°C)	Data of drilling	Surface temperature (°C)	pH	Other technical description
IM1	2.5	11.5	0.1–1.8	0–6 m: sands 6–11.5: tuff	68	August 1939	60 @ 1.68 m		Casing up to 7.7 m from well head
IM2	1.9	13.5	0.2–1.5	0–13.5 m: sands	68	August 1939	61 @ 31 m	6.5–8	Casing up to 6.15 m from well head
IM3	1.9	12.0	0.2–1.7	0–12 m: tuffs	69	August 1939		6.8–7.5	Casing up to 5.14 m from well head
IM4	2.9	16.5	0.2–1.7	0–16 m: tuffs	72	September 1939	72 @ 0.73 m.	6.8–7.5	Casing up to 5.76 m from well head
IM5	2.3	13	0.1–1.6	0–13 m: tuffs	84	September 1939	75 @ 6.9 m.	6.6–7.4	Casing up to 6.9 m from well head
IM6	6.6	17.3	3.5	0–17.3 m: clay and tuffs	60	September 1939		7	
T1	4.7	5	0.1–1		62			6.9–8.4	Casing up to 5 m from well head
T2	4.47	5	0–1.5		46			7–8.3	Casing up to 5 m from well head
T2A	5.9	6.20	0.1–1.8		55			7–8	Casing up to 6.2 m from well head
T3	4.6	6.20	0.1–2		58			7–8.4	Casing up to 6.2 m from well head
T3A	5.7	6.10	0.1–1.9		64			7.3–8	Casing up to 6.1 m from well head
T4	4.3	4.95	0.1–2.2		64			7–8	Casing up to 4.96 m from well head
T5	4.7	4.9	0.1–1.8		70			6.8–7.5	Casing up to 4.9 m from well head
T6	4.2	4.6	0–1		70			6.8–7.5	Casing up to 4.6 m from well head
T7	6.7	8	0–1.6		89			6.7–7	Casing up to 8 m from well head
T8	10.0	10.75	0–1.5		80			6–7.5	Casing up to 10.7 m from well head
T9	7.8	8.15	0.1–1.8		80			6.3–7.5	Casing up to 8.2 m from well head
T9A	8.2	8.5	0–4.8		90			6.7–7	Casing up to 8.5 m from well head
T10	10.24	11.5	0.1–1.5		81			6.6–7.6	Casing up to 10.9 m from well head

Penta and Conforto (1951).

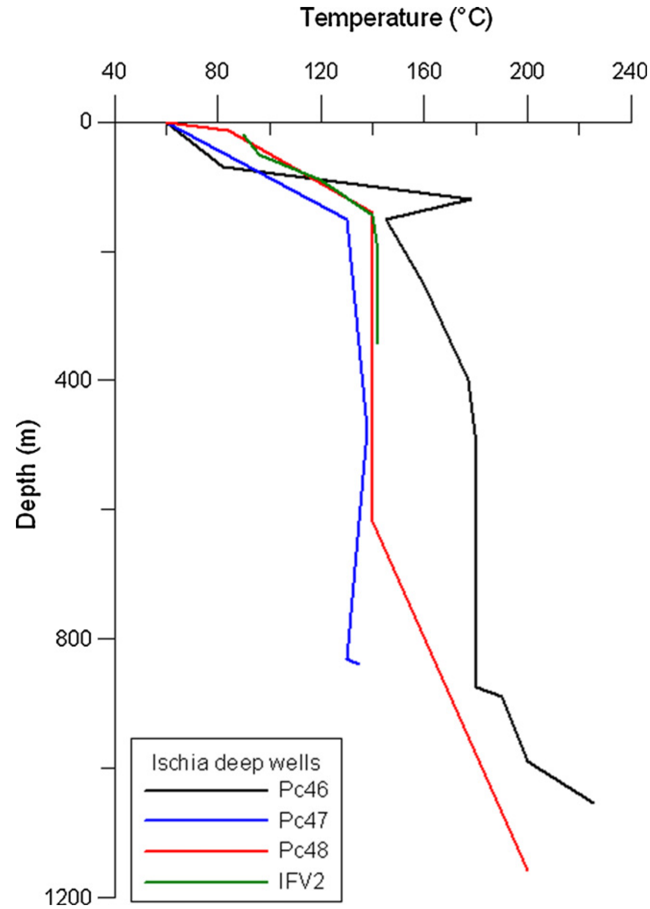

Fig. 15. Temperatures versus depth measured during the deep drilling at Ischia. After AGIP (1987).

mainly represented by a succession of lavas, tuffs, pumice, sandstones, siltstone and clay [87]. From 1890 m to the well bottom, dolomite rocks were encountered. The drilling allowed to identify different evolution stages of the volcano during Quaternary, with a new $^{40}Ar/^{39}Ar$ dating of the oldest volcanic activity which was estimated about 400 ky B.P. The volcanic activity since this period was also characterized by volcanic quiescence and marine sedimentation [18]. The whole emergence of the shoreline occurred about 37 ky B.P, mainly due to the sea level change during the last glacial period and deposition of the 60 m thick Campania Ignimbrite deriving from the 39 ky B.P. Campi Flegrei eruption. The Trecase 1 drilling represents the only example, in the Campania Plain, in which the Mesozoic basement carbonatic rocks have been encountered (Brocchini et al., 2001). Unfortunately, the expected temperatures for geothermal exploitation were not found, in fact the measured geothermal gradient was lower than the earth's average one (30 °C km^{-1}), with bottom well temperature of 51 °C (Fig. 16). Furthermore, the absence of hydrothermal alterations within the sampled rocks, demonstrate that, around the volcano, is not present a significant circulation of hydrothermal fluids.

The low thermal gradient measured within the Trecase 1 well was most likely due to the magmatic system type, probably composed by a series of shallow vertical dikes (2–4 km) which rapidly loose the heat by conduction and by water circulation. Relatively low temperature was also found during the more recent deviated drilling at Unzen active volcano, performed on 2004, just 9 years after its last eruption. A dike was sampled at 1.3 km of depth, within the 0.5 km wide volcano conduit, a zone consisting of multiple lava dikes and pyroclastic veins, where temperature was less than

Table 6
Synthesis of drilling at Ischia performed from the 1939 to 1943 at Forio site (southern island sector) (Penta and Conforto, 1951).

Well	Head well elevation (m a.s.l.)	Depth (m)	Water table (m a.s.l.)	Encountered soils (formation type)	Maximum temperature (°C)	Data of drilling	Water temperature (°C) above sea level	pH	Other technical description
ICA0	6.9	19.3	0.7–1	0–19.3 m: sands and tuffs	100	April 1939	95 @ 4.8 m	6.4–7	Rotary drilling. Casing up to 13 m from well head
ICA1	7.2	22.20	0.4–1.4	0–22 m: tuffs	120	October 1939	86–88 @ 1 m.	6.7	Wire Drilling. Casing up to 17.3 m from well head. Spontaneous geyser activity April 1940
ICA2	4.4	96.0	0.3–1.4	0–4 m: soil; 4–90: gray unconsolidated tuffs; 90–86: green tuff	128	October 11th 1939–June 8th 1940	60 @ 0 m	6.7	Wire Drilling Casing up to 27.75 m from well head.
ICA3	5.8	15.5	0.1–0.9	0–15.5 m: sends and tuffs	103	October 1939	93 @ 1 m	6–8	Casing up to 15.15 m from well head. Capacity during pumping test 6–1 l s^{-1}
ICA4	9.7	14	0.1–1	0–14 m: sends and tuffs	95	October 1939	93 @ 1 m	6–7.5	Casing up to bot Capacity during pumping test 3–4 l s^{-1} tom well.
ICA5	2.5	13.0	−0.9 to 1	0–13.00 m: sends and tuffs	113	October 1939	110 @ 0 m	6–7	Casing up to botto Capacity during pumping test 15–20 l s^{-1} m. well.
ICA6	2.1	10	0–0.7	0–10.0 m: sends and tuffs	76	November 1939		6.5–7.5	Casing up to bottom well.
ICA7	2.2	13	−0.1 to 1	0–30 m: type a; 30–70: type b; 70–80. type c	60	November 1939		6.8–7.1	Casing up to bottom
ICA8	11.4	19	0–0.80	0–24.30 m: type a	99	April 1940	95 @ 0 m	6–7	Wire Drilling. Casing up to 17.5 m from well Capacity during pumping test 6–7 l s^{-1}
ICA9	9.3	16.2	0.3–0.8	0–16.2 m: sends and tuffs	104	December 1941			Wire Drilling. Casing up to 17.5 m from well Capacity during pumping test 0–1 l s^{-1}
ICA10	6.12	20.0	0–0.8	0–20 m: sends and tuffs	111	June 1940	92 @ 0 m		Wire Drilling. Casing up to 17.3 m from well Capacity during pumping test 7–9 l s^{-1}
ICA11	11.94	19	0–0.9	0–45: type a	100	June 1940	96 @ 0.5 m		Casing up to 18 m.
ICA12	7.02	14.25	0.3–0.9	0–17: type a	100	June 1941	71 @ 0.5 m		Casing up to 13.5 m. Capacity during pumping test 10–15 l s^{-1}
ICA13	6.55	15.8	0–0.8	0–20: type a	97	Novembre 1941	77 @ 0 m		Casing up to 14.5 m. Capacity during pumping test 4–8 l s^{-1}

Table 6 (*Continued*)

Well	Head well elevation (m a.s.l.)	Depth (m)	Water table (m a.s.l.)	Encountered soils (formation type)	Maximum temperature (°C)	Data of drilling	Water temperature (°C) above sea level	pH	Other technical description
ICA14	7.05	18.6	0.2–0.6	0–20: type a	116	August 1942			Casing up to 17.7 m. Capacity during pumping test 14 $l\,s^{-1}$
ICA15	7.19	20	0.4–0.8	0–3.15: type a	100	August 1942			Casing up to 15 m. Capacity during pumping test 11–15 $l\,s^{-1}$
ICA16	7.14	20	0.5	0–4.15: type a	102	October 1942			Wire drilling. Casing up to11.1 m. Capacity during pumping test 13–14 $l\,s^{-1}$
ICA17	7.19	19.60	–	0–26.40 m: reworked tuff (green); 26.40–69.30: volcanic breccias and reworked tuff; 69.30–93: gray and green tuff; 93–110: altered tuff with breccia; 110–263.4: gray-green tuff with lava and pumice; 263.4–283.4: green tuff with breccia		October 1942			Casing up to 16 m.
ICA18	4.5	19	0.2–2.7	0–23 m: unconsolidated tuff; 23–78: volcanic breccia; 78–94: gray-green tuff; 94–132: altered tuff with breccia; 132–330: gray-green tuff with lava and pumice	100	June 1940	79 @ −0.5 m	6–7	Capacity during pumping test 7–8 $l\,s^{-1}$
S8	3.83	5.5	−0.2 to 1.2		40	Novembre 1939		7–8	Casing up to the well bottom
S9	3.89	5.5	−0.2 to 1.3		45	Novembre 1939		7–8	Casing up to the well bottom
S10	3.33	5.5	−0.3 to 0.8		88	Novembre 1939		6.7–7.8	Casing up to the well bottom
S11	2.95	5.5	−0.2 to 0.8		85	Novembre 1939		6.5–7	Casing up to the well bottom
S12	1.14	4.5	−0.1 to 1		32	Novembre 1939			Casing up to the well bottom

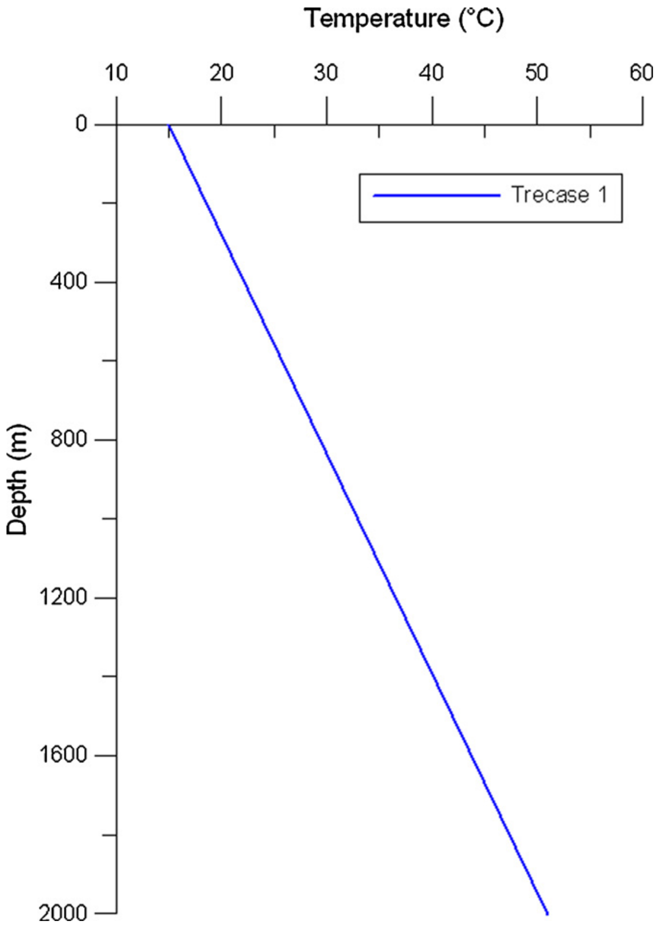

Fig. 16. Temperature versus depth measured during the drilling at Vesuvius (Trecase well).
After AGIP (1987).

200 °C. In this case the feeding dike of the 1991–1995 eruption had cooled from 850 °C to 200 °C in nine years (72 °C y^{-1}), mainly due to the hydrothermal circulation [102]. In the case of Vesuvius, the situation could be different because, if there is not large hydrothermal circulation, the central part just below the crater, down to several km of depth, could be still hot because representing the large volumes of intruded magma leading to recent eruption [103]. Such central plug below the main crater is marked in fact by very high rigidity, which should indicate magma solidification in the main rising conduits. However, by conduction alone such a solidification cannot be explained in terms of significant cooling, and it has in fact been interpreted, by De Natale et al. (2004) [103], as mainly due to marked gas exholution from magmas, with only modest decrease of temperature. If this model is true, the low temperatures encountered in the Trecase wells are simply explainable because the site is too far from the crater, below which should be concentrated the thermal anomaly due to rising magmas.

8. Temperatures, crust rheology and magma reservoirs location beneath Campanian volcanoes

The intermediate to deeper structure beneath the Campania volcanoes has been investigated since 1970 by seismic, gravimetric and aeromagnetic surveys [5,9,29,46,104–106]. At regional scale the Bouguer gravity anomaly data show a minimum centred over the Campanian Plain, in the Campi Flegrei area [26]. This is due to the refilling of low density pyroclastic deposits and to the occurrence of altered rocks of the Campi Flegrei caldera and surroundings. In this volcanic area no evidences of the magma emplacement at shallow level have been detected by the seismic survey, while an extensive partial melt zone at a depth of about 8 km beneath the Campi Flegrei caldera has been identified by the high-resolution seismic reflector in the Bay of Naples. This low velocity layer has probably an extension not less than 30 km^2, with a thickness of about 1 km [46,77]. Evidence of deep low density body, located at a depth of 8–10 km beneath Campi Flegrei area, was just inferred from gravity and aeromagnetic data by Rapolla et al., 1989 [9]. A similar magma body was recognized by the TOMOVES experiment, beneath the Vesuvius, at about 9–10 km of depth [29], while shallower magma reservoirs did not detected. Otherwise, the method used in the seismic investigations does not allow the detection of magma bodies with a volume less than 1 km^3.

At Ischia, a relative maximum Bouguer anomaly in the southwestern sector of the island was observed on the basis of gravimetric data [104,105]. An intense magnetic anomaly was also measured in the western of Ischia. On the other hand, at local level, a low value of magnetic susceptibility was recorded in the centre of the island and this was interpreted to be the consequence of high temperatures due to the presence of hot magmatic bodies at shallow depths [65,105]. Despite the numerous geophysical investigations performed since 1970 in the Campanian volcanic area, the presence and location of possible shallow magma bodies (<8 km), which could supply the large heat flow measured at Ischia and Campi Flegrei, has not yet univocally defined. Otherwise, the measured temperatures at different depth can furnish further important constrains to understand the rheology of the shallow crust and possible magma batches. The data recorded during the geothermal exploration fields at Campi Flegrei, Ischia and Vesuvius, have been utilized by various authors to provide a geological and geophysical structure of campanian volcanoes shallow crust. These data have also been employed for the calibration of geophysical surveys, particularly for the correlation between seismic wave velocity and rocks density at different depth [29,46,65,74,76,107]. The integration of the temperatures, measured within wells that go deeper than 1 km [3], with the seismic and gravimetric data represents a reliable constrain for crustal dynamic and rheology assessment. In fact, the deviation of temperature/depth profile from the average Earth one (30 °C km^{-1}) depends on different conditions such as the thickness of the crust and its thermal conductivity, the heat production at depth, the fluids circulation, the age and tectonic history of the lithosphere. In active volcanic area is generally observed an increase of temperature variation with depth and, of course, an increase of the heat flux in respect to the average for all continents (65 ± 1.6 mW m^{-2}) [108]. This is due to the upward migration of the Moho and to the magma rising within the crust at shallow levels (few kilometers). In the south of Italy, at regional level, the temperature distribution with depth show that the heat flow and the crust temperatures increase from Adriatic to Tyrrhenian Sea direction (Fig. 17) [13]. According to the interpretation of volcanic activity of the western Tyrrhenian margin (which start about 2 My ago) [7], this is due to the mantle upwelling and sea floor spreading, which produce a thinning of the crust and the increasing of the heat flow from east to west. Heat flow at Campi Flegrei was calculated by Corrado et al. (1998) [109], who show very high values at Mofete (160 mW m^{-2}), S. Vito and Mt. Nuovo (80 mW m^{-2}) and Agnano (120 mW m^{-2}). At Ischia we calculate the heat flow ($q = k \times \Delta T/l$) considering the temperature measured within deep wells (Pc 46, Pc 47 and Pc 48) located in the south-western sector and setting the thermal conductivity (k) for shallow volcanic environments equal to 1.5 W m^{-1} °C^{-1} [110]. The results show that also this sector is characterized by a very high heat flow equal to 588 mW m^{-2} (Pc 46), 620 mW m^{-2} (Pc 47) and 560 mW m^{-2} (Pc 48). At regional level, the shallow thermal plume which is located in the western part of Campanian volcanoes is also highlighted by

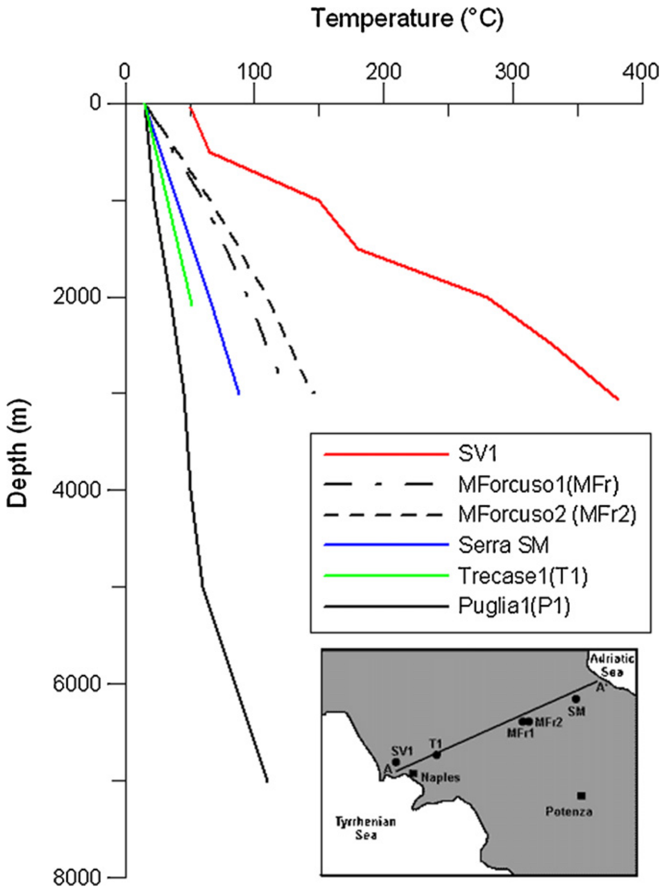

Fig. 17. Temperature versus depth measured in the deep wells along a section from Adriatic to Tyrrhenian sea. The geothermal gradient, except for anomalous low temperature at Vesuvius (Trecase), decrease from Adriatic towards Tyrrhenian sea.

Modified after Della Vedova (2001).

the temperature distribution with depth, along the section which crosses the Ischia island, the Campi Flegrei caldera and the Vesuvius (Fig. 18). In fact, the isotherm of 200 °C is located at a depth of about 1–1.5 km, going from Ischia towards Campi Flegrei, and deepen towards Vesuvius down to about 6 km close to the volcano. Local hot plumes have been observed at Ischia and Campi Flegeri depending of the local geology and fluids circulation (Fig. 19a–c). Fig. 19a shows a temperature high below the Mofete geothermal field. At Ischia, in the south-western sector, a possible doming structure caused by lava intrusion, after the MEGT eruption (55 ky), produced bending of the upper layers and the rising of the isotherm at shallow depth (Fig. 19b). Also the southern sector is characterized by a constant high temperature at the surface (80–100 °C) along the Maronti shoreline (Fig. 19c). Thus, short wave-length variation of the isotherms (hundreds of meters) can be related to shallow magma batches and hot fluids upwelling, while long-wave variations (tens to hundred of kilometers) can be linked to the heat provided by deeper and larger magma bodies and to the rising of the Moho discontinuity. As described above and in the previous sections, the investigated volcanic areas are characterized by different dynamics and shallow structure. Ischia and Campi Flegrei caldera have been marked during the volcanic history by large ground uplift. Starting from about 55 ky, the island of Ischia has undergone an uplift of about 800 m, at a rate of about 3 cm y^{-1}, which formed the present Mount Epomeo resurgent block, in the centre of the island [37,58,65,68,99]. At Campi Felgrei, different periods of uplift have been identified during Roman times, before the 1538 eruption, and in recent times, during the 1970–1972 and 1982–1984 unrests (with rate of few millimeter per day), with a total uplift of some tens of meters. These periods are superimposed to a general subsidence trend at a rate of 1.1–2 cm y^{-1}. In both volcanic areas, and mainly at Ischia, there is the presence of a vigorous hydrothermal system, with maximum surface temperature of about 100 °C. Furthermore, at Ischia and Campi Flegeri the seismicity recorded in historical time is located in the first 2 km and 4 km of depth, respectively, probably reflecting the transition form brittle to ductile behavior of rocks at these depths [31,65,111–113]. All these elements are distinguishing of the dynamic of shallow magma bodies. Conversely, the Vesuvius is characterized by the presence of a

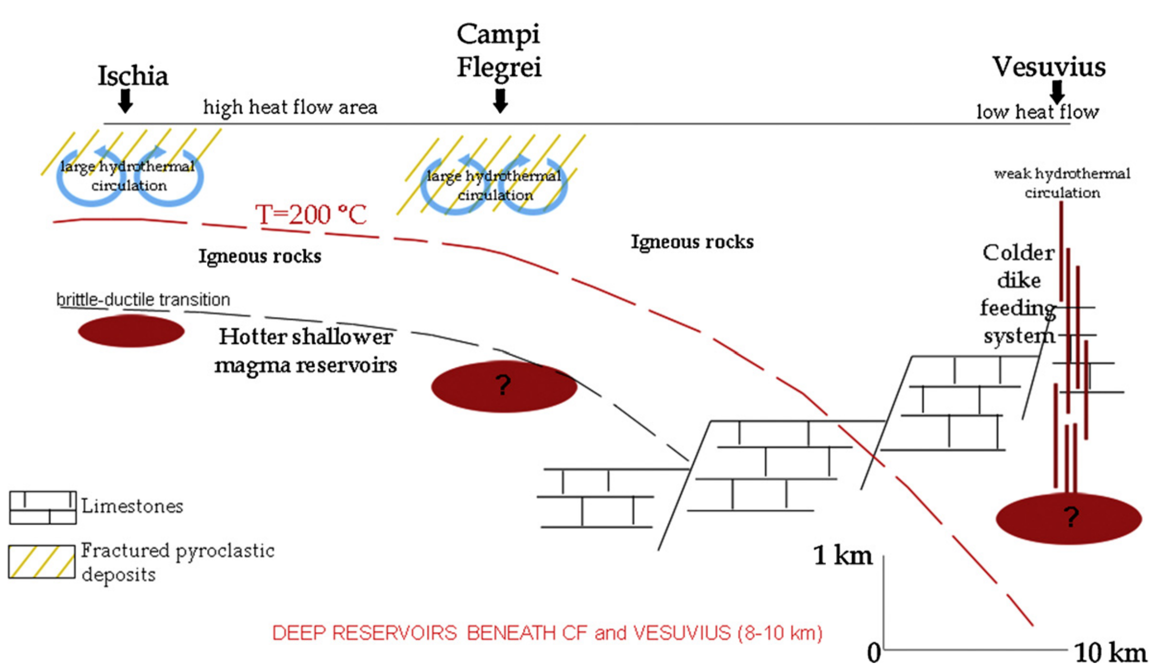

Fig. 18. Sketch of the shallow crust beneath Campanian volcanoes along a section from Ischia to Vesuvius deduced from gravity, seismic and wells data. It is reported the regional 200 °C isotherm and the depth of the brittle to ductile transition ($T > 350$ °C).

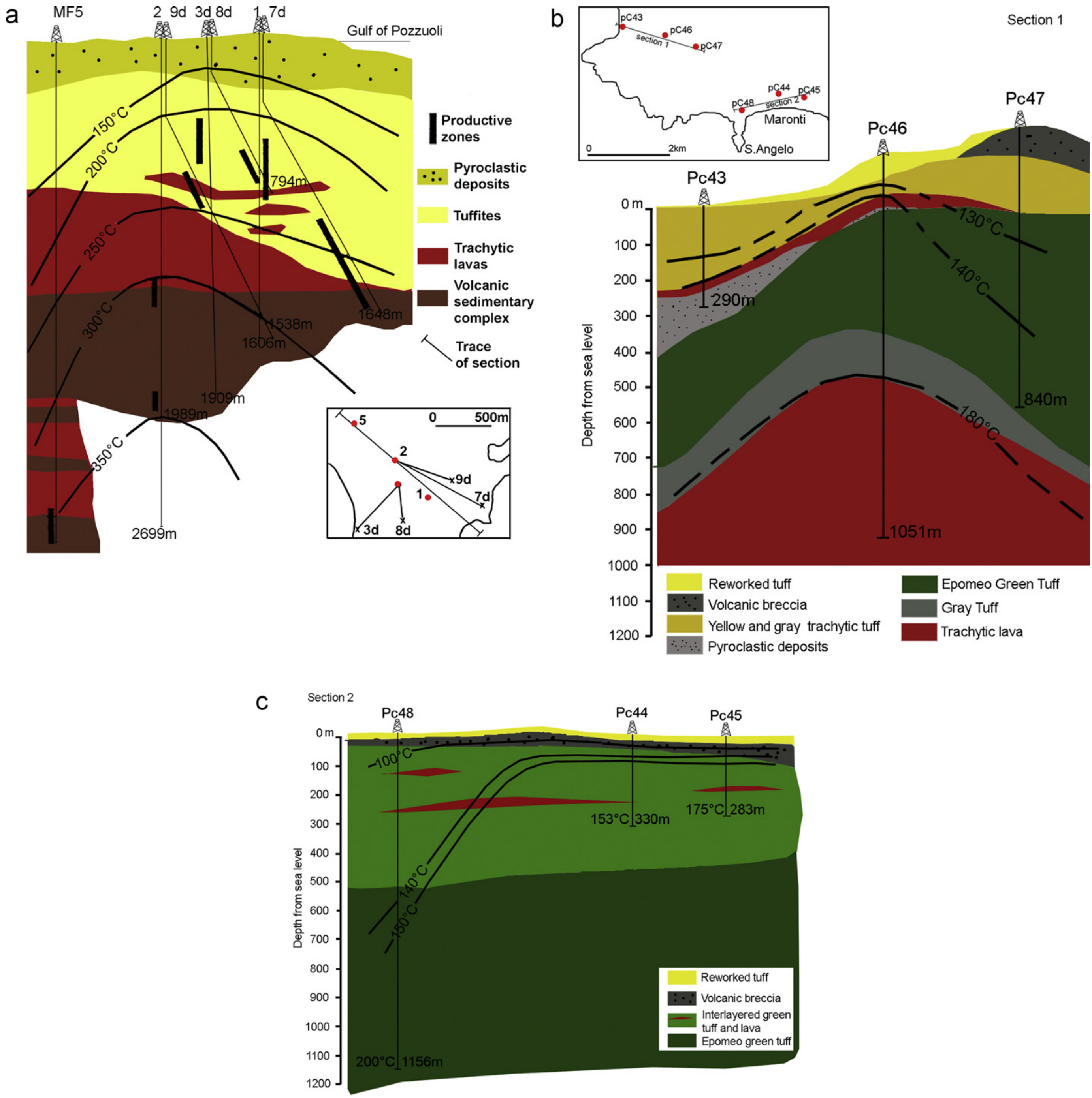

Fig. 19. (a) Isotherms beneath the Mofete geothermal field deduced from wells data. It is also reported the startigraphy and productive zones (modified after AGIP, 1987). (b) Isotherms beneath the south-western sector of the Ischia island and stratigraphy deduced from wells data. The heat plume is possible related to the local shallow trachytic intrusion occurred after the MEGT eruption (55 ky) which deposited the Epomeo Green Tuff. (c) Isotherms beneath the south sector of the island and stratigraphy deduced from wells data. A stable temperature zone is identified along the Maronti shoreline.

shallow (1–2 km) cooled dikes system and/or small magma batches which fed the last volcanic activity since 1944 [31,83,103]. For this reason the residual heat is concentrated just along the crater axis (roughly a cylinder with 300 m of diameter) where hydrothermal circulation occurs. The lack of a large radius hydrothermal system is confirmed by the very low temperature measured in the Trecase well (3.8 km far from the carter axis). Larger and hotter fluids circulation probably occurs deeper than about 2 km [83]. The absence of shallow (1–2 km) large scale hot groundwater motion at Vesuvius, probably produce a mostly conductive regime (instead of advection) of the heat supplied by the deep reservoir. In this case is not surprising to find very low temperature at shallow depth, while an increase of temperature is expected closer to the magma reservoir. A theoretical demonstration of such statement can be performed, firstly for Vesuvius, by using the relation showing the increase of temperature with depth and time, for the simplified assumption of one dimensional unsteady heat conduction in an infinite region [108]. This assumption is suitable for the case of a sill intrusion having heat content per unit area (Q) equal to:

$$Q = \rho[c(T_m - T_0) + L]2b \qquad (1)$$

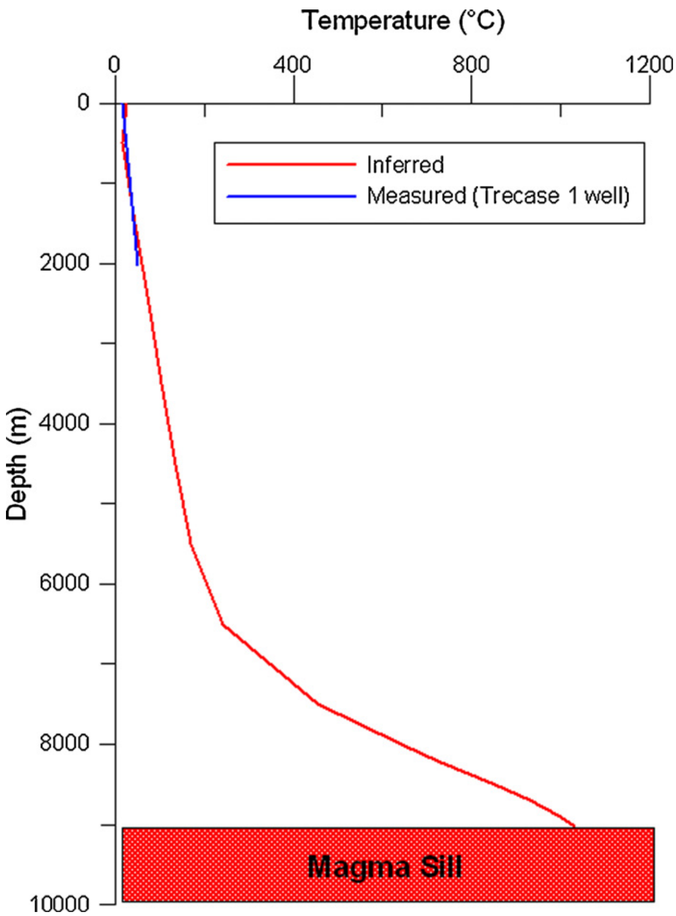

Fig. 20. Comparison between the conductive curve obtained by Eq. (2) for a sill intrusion 8–9 km depth, at a time t = 25 ky and the measured shallow temperature profile at Vesuvius.

where ρ is the rocks density, c is the specific heat of magma, T_m is the magma temperature, T_0 is the temperature of surroundings rocks, L is the latent heat of fusion and b is the thickens of the sill. The last value is inferred by the results of the seismic tomography at Campi Flegrei and Vesuvius and by the gravity data, which provide an average thickness of about 1 km [9,29,46,106]. Furthermore, we consider an initial condition of undisturbed crust, with geothermal gradient of 30 °C km^{-1}. After the sill intrusion, at depth of 8–10 km, the temperature distribution varies with time, perpendicular to the sill. The temperature distribution $T_{(y,t)}$ is given by the following equation [108]:

$$T_{(y,t)} = \frac{Q}{2\rho c\sqrt{\pi \kappa t}}\, e^{-y^2/4\kappa t} \tag{2}$$

where k is the thermal diffusivity, t is the time, y is the distance from the sill. For the calculation of Q, from Eq. (1), we set an average ρ = 2300 kg cm^{-3}, c = 1 kJ kg^{-1} K^{-1}, L = 350 kJ kg^{-1}, T_{m} = 1000 °C (1273 K) and T_0 is 300 °C (573 K) close to the sill at the initial condition [29,31,74,75,103,107,108,110,114]. Thus, the value of Q is equal to 6×10^{12} J m^{-2}. Setting, in the Eq. (2), $k = 10^{-6}$ m^2 s^{-1} [108], we estimate the change of temperature as a function of the distance from the sill. In Fig. 20 we show an example of the temperature/depth profile obtained from Eq. (2), by setting t = 25 ky, which corresponds to the time of the oldest emerged volcanic activity of Somma-Vesuvius volcanic complex. This is compared, just for the first 2 km of depth, with those obtained from the temperature measured within the Trecase 1 well, showing a generally reasonable fit. The obtained result supports the hypothesis that the shallow structure of Vesuvius is formed by a cooled dikes system or small magma batches and that the hydrothermal shallow system (0–2 km) is characterized by relative low temperature. Within and below the carbonatic layer, down to 2 km of depth, an isolated cell hydrothermal system with higher temperature could exist [83].

At Ischia island and Campi Flegrei, the persistence of a large hydrothermal system produces a perturbation of temperature distribution within the shallow crust, with very high geothermal gradients (150–200 °C km^{-1}). This indicates that possible magma bodies induced the observed large scale groundwater motion, but also in these volcanic areas is not yet definitely clear the presence of shallow magma reservoirs. Recent studies of Ischia island volcano dynamics agree with the presence of a laccolith beneath the centre of the island, whose top is locate at about 2 km below the surface [65,67,68]. The magma intrusion, which started from 55 to 33 ky ago, produced the uplift of the central block, and the partial exhumation of the active magmatic hydrothermal system [68]. At Ischia, the measured geothermal gradients within the deep wells show a rapid increment down to about 200 m, and a steady temperature zone between about 200 and 900 m (Fig. 15). This stable reservoir has a temperature of about 180 °C (Pc 48 well) and 130–140 °C (Pc-46-47 and IFV2 wells). In this case, since the temperature distributions at depth are certainly dependent on the hot fluid circulation, we can study the upwelling flow above the intrusion, by using the approximation of one-dimensional advection of heat in a porous media. In the hypothesis of heat advection by the groundwater motion, the temperature as a function of depth is depending on various factors such as: temperature difference between reservoir and surface ($T_r - T_0$), fluid density (ρ_{f}) and its specific heat (c_f), Darcy velocity of the fluids in the porous media (v), solid matrix thermal conductivity (λ) and depth (y). Thus, the temperature distribution with depth (T) is given by the following analytical solution [115,108]:

$$T = T_r - (T_r - T_0) \cdot \exp\left(\frac{\rho_f c_f v}{\lambda} y\right) \tag{3}$$

As reported above by the analysis of the geotherms within the deep well at Ischia, we set the steady temperature of the shallow reservoir equal to 180 °C (Pc 48 well) and 140 °C (Pc-46-47 wells), respectively, and ρ_f = 1000 kg m^{-3}, c_f = 4.185×10^3 J kg^{-1}, λ = 3.35 W m^{-1} C^{-1} and $v = 6.7 \times 10^{-8}$ m s^{-1}. The two latter values are the ones generally utilized for volcanic environment [108,116,117]. The average surface temperature (T_0) at Ischia is evaluated at about 60 °C. The comparison of the obtained theoretical curves with the measured gradient is shown in Fig. 21. The good agreement of the curves confirms the occurrence of geothermal advection beneath the island. Furthermore, if the flow is driven by the buoyancy of the hot water, we can also use the Darcy velocity (v) to estimate the permeability (K) of the system, assuming that the flow is laminar and the amount of pressure gradient in excess of the hydrostatic value is negligible in the upwelling flow. This indirect method is very useful to estimate the large scale permeability, when the analysis is performed over a dimensional space that is larger than the dimension of the porous or spacing fractures through which the fluid flows. The permeability K as a function of Darcy velocity is given by [108]:

$$K = \frac{v\mu}{\alpha_f \rho_f g (T_r - T_0)} \tag{4}$$

where μ, α_f and ρ_f are the viscosity, the coefficient of thermal expansion and the density of the fluid, respectively. The obtained values of permeability are 6×10^{-16} m^2 and 2×10^{-15} m^2 for the reservoir temperature of 180 °C and 140 °C, respectively. The results are in agreement with the average permeability values inferred from theoretical fluid-dynamical models of ground deformation data at Campi Flegrei and other volcanic environments [57,118]. In addition to the heat in the crust maintained by hot

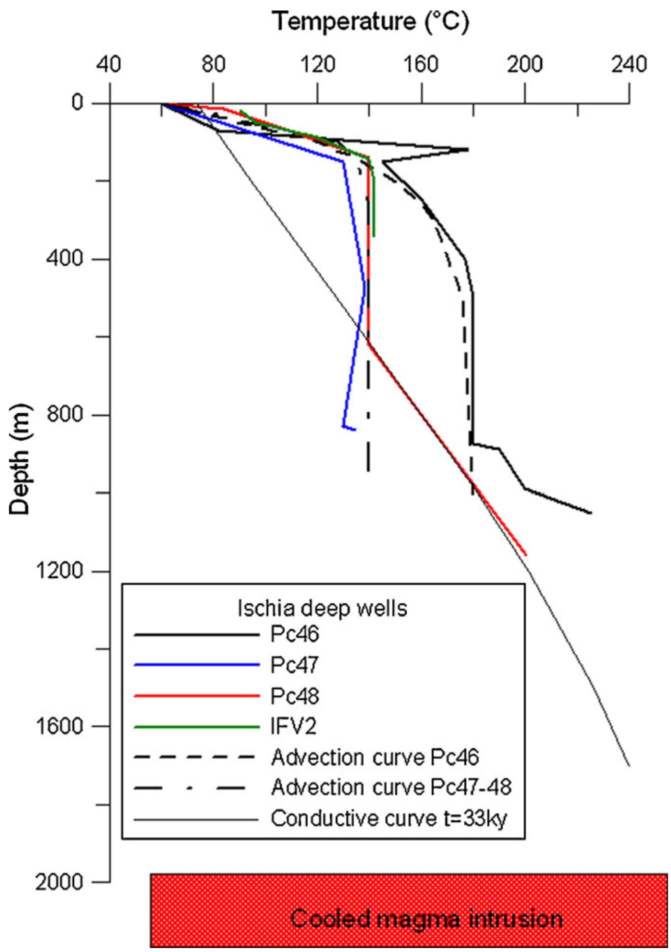

Fig. 21. Comparison between advection and conductive curves with the temperatures measured in the deep wells at Ischia (see text for details).

fluids circulation beneath the island of Ischia, we have to consider also the conductive heat due to magma intrusion at shallow depth, by using Eqs. (1) and (2). The heat content per unit area (Q) is evaluated considering that initial conditions are those that followed the great eruption of the Mount Epomeo Green Tuffs (55 ky), which certainly produced a large amount of heat in the shallow crust. Thus, we set the difference of temperature between the reservoir and the surroundings ($T_m - T_0$) to roughly 100 °C (373 K), while the density of rocks is assumed as 2100 kg m^{-3}, obtaining a value of $Q = 1.6 \times 10^{12}$ J m^{-2}. By Eq. (2), we evaluate the temperature distribution as a function of depth and time, setting $t = 33$ ky, which is the time of resurgence onset in the island indicating the occurrence of shallow magma intrusion, at about 2 km of depth [58,63,65,68,119]. This magma body is nowadays partially cooled, with temperature at the top probably above 350 °C. The obtained curve (conductive curve) is compared with the measured temperature within deep wells (Fig. 21). The result is interesting, since the curve fits well the deeper part of the geothermal gradients of Pc48 well. This lower part, which is characterized by a linear increase of the temperatures can be hence assumed as due to a conductive regime. With this assumption, the difference between the Pc46 well temperature curve and the conductive curve could represent the average increment of temperature due to the hydrothermal circulation.

At Campi Flegrei, the temperature versus depth distribution measured in deep wells, show a different pattern with respect to Ischia, which is probably associated to the presence of various permeable layers [3]. The lack of a unique shallow fluid reservoir does not allow the occurrence of steady temperatures within

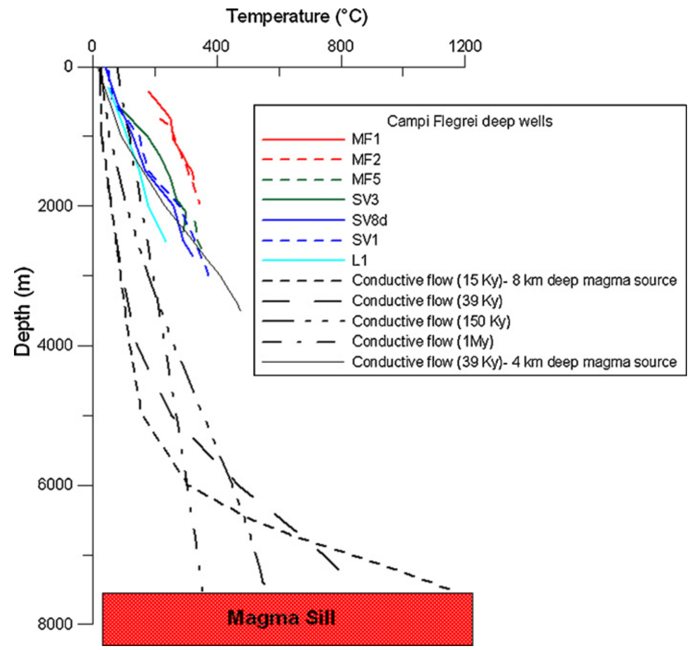

Fig. 22. Comparison between conductive curves, for different time of sill emplacement, with the temperatures measured in the deep wells at Campi Flegrei (see text for details).

a consistent interval of depth and thus Eq. (3) is not applicable. Several models of geothermal circulation and resurgence in the Campi Flegrei caldera highlight that hot fluids, which have been partly responsible of the uplift recorded during the 1970–1972 and 1982–1984 unrests, circulate mainly within the inner caldera rocks [31,50,54,120]. This is also supported by the higher temperature gradients recorded in wells located inside the caldera itself (MF1-2-5, SV1-3-8d wells), with respect to the lower and roughly linear gradient of L1 well, that is located outside of the caldera. For this reason, we assume that the temperature–depth profile of L1 is mostly due to a purely conductive transport of the heat provided by the magma reservoir and only in minor part to hot fluids circulation. Assuming the same parameters of the deep magma source adopted for the case of Vesuvius ($Q = 6 \times 10^{12}$ J m^{-2}), located at a depth of 8 km, we calculate the conductive temperature–depth curve for different times which correspond to 15 ky (NYT eruption), 39 ky (CI eruption), 150 ky (older Ignimbrite eruptions), 1 My (older volcanic activity of Campania volcanism), [7,22,36,38,121] (Fig. 22). Comparison of the obtained curves with the measured temperatures–depth profile of the wells, shows that a conductive heat transport, also acting at the longer time scale, is not sufficient to get the nowadays thermal state of the shallow crust, also assuming a shallow magma source (4 km). This result is in agreement with the Campi Flegrei caldera thermal model proposed by Wohletz et al. (1999) [107]. Only for the L1 well, the measured temperatures are similar to those obtained by conductive heat transport after 1 My. Then, the thermal state outside the caldera could be mainly linked to the long term conductive heat propagation from the deep source, while the higher gradients within the caldera are related to hot fluids circulation.

9. The assessment of geothermal resource of Campanian volcanoes

A preliminary evaluation of geothermal resources was made during the AGIP-ENEL drilling at Campi Flegrei (AGIP, 1987). It did not take into account the whole geothermal potential of the area, but considered the available electrical energy for the productive

Table 7
Data from: Penta and Conforto (1951), AGIP (1987), Schon (2004), Smith (2006).

	Area (m^2)		Layer thickness m (depth interval)	Volume (m^3)	ρ ($kg\,m^{-3}$)	T_i average (K)	ϕ
Mofete	2×10^6	1	500 (500–1000)	10^9	1759	503	0.28
		2	200 (1800–2000)	0.4×10^9	2459	613	0.1
		3	200 (2500–2700)	0.4×10^9	2459	613	0.1
S. Vito	3×10^6	4	500 (0–500)	1.5×10^9	1759	351	0.3
		5	500 (100–1500)	1.5×10^9	1759	411	0.25
Ischia	17×10^6	6	600 (300–900)	10×10^9	2000	273	0.3

wells of Mofete area (Mofete 1, 2, 7d and 8d), which amounted to some tens of MWe. Further evaluation of the geothermal potential at Campi Flegrei and Ischia is reported by Marini et al. (1993) [101], taking into account the well temperature profiles and the geochemical fluid composition. The results of the above analysis highlighted the feasibility of geothermal exploitation at Campi Flegrei and Ischia, but this possibility was abandoned for both technical and political reasons. The development, in recent time, of new technologies for geothermal energy production, allows the exploitation also of medium enthalpy resources ($T < 150\,°C$). For this reason we consider appropriate a new assessment of the geothermal potential of Campi Felgrei and Ischia, as stored into the shallow crust. We use here the classical and most commonly used method for geothermal potential estimation, the *volume method* proposed by Muffler and Cataldi (1978) [122]. This requires, in the first step, the calculation of the heat stored in a certain volume of the crust to a specific depth. The subsurface volume is sub-divided in several units based on hydrogeological and geothermal considerations, taking into account the temperature and porosity trends with depth. The amount of total geothermal heat stored into a certain volume (Et) is equal to the sum of heat stored in the rocks (E_r) and in the fluids (E_w), following the relationships [122]:

$$E_r = V_i \cdot (1 - \phi_i) \cdot \rho_{ri} \cdot C_{ri} \cdot (T_i - T_0) \tag{5}$$

$$E_w = V_i \cdot \phi_i \cdot \rho_{wi} \cdot C_{wi} \cdot (T_i - T_0) \tag{6}$$

where V_i and ϕ_i are the volume and the average porosity of the ith unit, ρ_{ri} and C_{ri} are the density and the specific heat capacity of the rocks of the ith unit, ρ_{wi} and C_{wi} are the density and the specific heat capacity of the fluids contained in the ith unit, T_i is the average temperature of the ith unit, and T_0 is the reference temperature, which is taken to 298 K in this example. Moreover, only a fraction of the geothermal heat stored in the subsurface can be extracted. This is strictly correlated to the characteristics of the geothermal reservoirs, which are difficult to evaluate by numerical models [123], thus the fraction of actual extractable energy (Ee) can be known only upon completion and discharge of geothermal wells. Empirical data show that a recovery factor $Rf = Ee/Et$ can be adopted to avoid this limitation. Muffer and Cataldi (1978) [122], after a review of heat extraction from geothermal systems, argued that the value of Rf ranges from 0.05 to 0.15 (5–15%), and that this value increases from liquid-dominated to vapor-dominated systems, respectively [124,125]. Furthermore, the volume method considers only the *status quo* underground [122], without evaluate the heat recharge coming from higher depths, where magma reservoirs are located. Nevertheless, several modelings of geothermal systems, as well as experimental results, have shown that the recovery of heat during few tens of years of exploitation generally does not exceed 10–20% of the heat extracted from the storage alone [122,125]. Since the volume method considers a recovery factor of 5–15%, in general, the replenishment of the geothermal resource could be guaranteed by the 10–20% of the heat resupply. By using Eqs. (5) and (6) we evaluate the geothermal potential, for Campi Flegrei and Ischia, while this evaluation is neglected for Vesuvius were the geothermal gradient, down to 2 km of depth, is not relevant for our purpose. For Campi Flegrei, we consider two main areas (Mofete and S. Vito) for which the parameters of deep geological reservoirs (temperature, porosity and density) are available [3,74,76,126]. Three formations, with hot fluids circulation, have been identified at Mofete: 500–1000 m with 20% vapor; 1800–2000 m with 40% vapor; 2500–2700 m probably vapor dominated. The surface area has been delimited by the extension of the well fields and is assumed equal to 2 km^2. At S.Vito (SV1 well), we recognize that the temperature gradient with depth (dT/dh) is very low at the depth interval of 0–500 m and 100–1500 m, where is reasonable to suppose the occurrence of more permeable layers with fluids circulation, which accounts for the homogeneous temperatures. The S. Vito area, where the wells are located, is considered of about 3 km^2.

At Ischia, the high temperature gradients of 150–220 °C/km^{-1}, measured in the wells of the south-western sector of the island [84], and the intense surface thermal activity (springs, fumaroles) reveal the presence of a vigorous hot hydrothermal system at shallow depth. Fractured lava layers could represent the main hydrothermal aquifer, which is likely developed until a depth of 2 km (Chiodini et al., 2004) where temperatures exceed the critical point of the water (374 °C). Furthermore, the temperature data of Pc46-47-48 wells reveal a steady temperature with depth from 300 to 900 m, where fluid circulation occurs. Also according to the stratigraphic and geochemical data [3,127], we consider that the shallow hot fluids reservoir, at Ischia, has a minimum vertical extension of about 600 m. In addition, the distribution of fumaroles and hot springs at the surface (with $p_{CO_2} > 0.10$ bar) suggests that the areal extension of geothermal reservoir is about 17 km^2 [101,127]. The specific heat capacity of Ischia rocks inferred from literature is $Cr = 0.9\,kJ\,kg^{-1}\,K^{-1}$ [110]; while for fluids we consider the value of the water $Cwr = 4.19\,kJ\,kg^{-1}\,K^{-1}$ and $\rho = 1000\,kg\,m^{-3}$ [128]. All the other parameters of Eqs. (5) and (6), for Campi Flegrei (Mofete, S. Vito) and Ischia, are reported in Table 7.

The results of application of Eqs. (5) and (6) are shown in Table 8. We apply a recovery factor Rf to the total energy for each area equal to 0.1, which represents an average estimation of the realistic values based on world-wide experience [122]. The total heat energy stored in the Mofete geothermal reservoir is equal to 1.08×10^{17} J, while the recoverable energy (Ee) is equal to 3.7 GWy. A value of 7.8×10^{17} J ($Ee = 2.7$ GWy) is obtained for S. Vito area. The total heat energy ($Et = 6.4$ GWy) is not all recoverable for electrical production. Usually, a cut off of fluids temperature is posed at 130 °C [128], above which it is generally assumed a good efficiency of geothermal plants for electrical production (although the actual lower limit for our climates is around 90 °C). Thus, subtracting the contribution of fluids with temperature $T < 130\,°C$, we obtain a value of 5.7 GWy. These values are similar to that calculated by Chiodini et al. (2001) [129] for the neighboring crater of Solfatara, using the surface thermal flux method. The former authors find that, on the basis of CO_2/H_2O ratio measured in high-temperature fumaroles inside the degassing area of Solfatara (roughly in the centre of Campi Flegrei caldera), the total thermal energy flux is $1.19 \times 10^{13}\,J\,d^{-1}$. The investigated area has an extension of about 1.4 km^2 [129,130]. The obtained energy, allowing for a recovery

Table 8
Evaluation of recoverable energy at Campi Flegrei and Ischia.

Mofete	E_r layer 1 (J)	E_r layer 2–3 (J)	E_w layer 1 (J)	E_w layer 2–3 (J)	*Ei*-tot (J)	*Ei*-tot (kWh)	*Ei* recoverable (GWy)
	2.34×10^{17}	5.01×10^{17}	2.40×10^{17}	1.06×10^{17}	1.08×10^{18}	3.00×10^{11}	3.7
S. Vito	E_r layer 4 (J)	E_r layer 5 (J)	E_w layer 4 (J)	E_w layer 5 (J)	*Ei*-tot (J)	*Ei*-tot (kWh)	*Ei* recoverable (GWy)
	8.81×10^{16}	2.01×10^{17}	1.76×10^{17}	3.12×10^{17}	7.77×10^{17}	2.16×10^{11}	2.7

Ischia	E_r layer 6 (J)	E_w layer 6 (J)	*Ei*-tot (J)	*Ei*-tot (kWh)	*Ei* extractable (GWy)
	1.70×10^{18}	1.67×10^{18}	3.40×10^{18}	9.44×10^{11}	11

factor of 0.1, corresponds to 5 GWy. This result is interesting, since the values of extractable energy related to similar geothermal areas (for size and geological features) within the Campi Flegrei caldera, show that the volume method is roughly comparable with the surface thermal flux one. At Ischia, the total thermal energy, which is related to a shallow reservoir whose temperatures are above 130 °C, is equal to 3.4×10^{18} J, corresponding to 11 GWy of recoverable energy. Finally, the obtained results for the total energy stored in the geothermal reservoirs are compared with the values of the heat content per unit area (Q) previously calculated for the magma reservoirs of Campi Flegrei ($Q = 6 \times 10^{12}$ J m^{-2}) and Ischia ($Q = 1.6 \times 10^{12}$ J m^{-2}), taking into account the related surface areas (total surface for S.Vito and Mofete = 5 km^2; total surface Ischia 17 km^2). We obtain a value for both the area Q = $\sim 3 \times 10^{19}$ J. This is one order of magnitude larger then the values calculated with the volume methods. Assuming that the evaluation of heat content per unit area is corrected, the lower values obtained with the volume methods can be ascribed to the variation of the entropy of the whole thermodynamic system.

10. The exploitation of geothermal resource in Neapolitan area

The most important result coming from the analyses performed in the former paragraph is the large amount of recoverable energy computed for Campi Flegrei and Ischia. It totals about 16 GWy of recoverable 'thermal' energy (16 GW of available power). Considering a minimum estimation for the efficiency of geothermal electric power plants of 0.1 (which is a minimum value obtained for very low temperatures around 100 °C, while for dry steam high enthalpy power plants it can be higher than 0.4) we got a minum power estimation of 1.6 GW, which is about double than the installed electrical power in the Tuscany geothermal areas. This means that the potential of Neapolitan volcanic area is about the same order of magnitude with respect to the actually exploited part of Tuscany. Neapolitan volcanic areas are however characterized by high urbanization, land value and huge geothermal potential, with high enthalpy resources often found at few hundreds meters of depth. The results from drillings at Mofete area show that high enthalpy resources can be found starting from depths as low as 400 m, whereas minimum temperatures exploitable for power generation (T100°) can be found also at few tens of meters of depth in areas like Campi Flegrei and Ischia, and at few hundreds meters of depth in most of Neapolitan area. Although high urbanization represents an obvious problem for a geothermal exploitation based on large power plants like in Tuscany Region (Larderello-Amiata), other exploitation models can fit better the features of the area. Firstly, the presence of a large urbanization just in the site of abundant and shallow low enthalpy resources naturally call for the direct use for heating and cooling. In fact, the availability of shallow resources practically at any site of the urban area makes very profitable the direct use of geothermal heat, which does not need the building of long and costly pipelines. Furthermore, the best model of electrical energy production at this area should be with diffuse networks of small to medium plants with almost negligible emissions and total reinjection. For medium enthalpy resources, this can be obtained by the use of binary power plants (with ORC or Kalina cycle) which, for the climate conditions of this area can work well with water down to about 100 °C, allowing efficient condensation of the binary fluid at local wet-bulb temperature. For high enthalpy resources, exploitation should be made with dry steam or flash plants (depending from the balance water/steam in the fluids) with recondensation of steam out of the turbines, and almost total re-injection in the reservoir. The recondensed fluid, before the reinjection, could be driven in a further binary cycle (hybrid plants, see De Pippo, 2005 [131]) or into a pipeline for thermal co-generation. Both of such cycles help to improve the efficiency of exploitation. An appropriate size for such a diffused system of small power plants would be in the range 1–10 MW. The modern technology for geothermal exploitation has also reduced the impact of small to medium size plants on the landscape; for instance, the binary power plant located in Nevada, with a net power of 14 MW, has a dimension less than 200 square meters [131]. The exploitation of reservoirs located at very shallow depth, as largely present at Campi Flegrei and Ischia, would also make completely negligible any risks of induced seismicity which, however, is already practically negligible during exploitation of natural hydrological reservoirs. At Campi Flegrei, in particular, there is evidence for almost complete absence of seismicity in the first kilometers of depth except some very small seisms (ML < 1) generally ascribed to geothermal system perturbations.

11. Conclusions

The history of geothermal researches in the Campanian volcanoes shows that, from 1930 to the middle 1980, a strong pulse was given to the exploration by using drillings and geophysical surveys. Although the main goal of the drillings was the assessment of the geothermal resource, in order to understand the feasibility of its exploitation for thermal and electrical uses, after the abandon of exploitation plans in the mid 1980s, the main use made of geothermal data and drillings has been for volcanological purposes. The period of geothermal explorations, for such reason, was characterized by a great pulse to the volcanologicalstudies, driving a hugeimprovement of knowledge about volcanic processes and related risk of eruptions in the highly urbanized area of Naples and neighborings. The risk problem emerged particularly after the two unrests episodes occurred at Campi Flegrei caldera, in 1970–1972 and 1982–1984, which indicated the possibility of an imminent eruption, pushing the local authorities to evacuate the town of Pozzuoli [31]. The temperatures measured in the wells (down to a maximum depth of about 3 km), joined with the stratigraphy and the geophysical data inferred from the drillings, provided important information to evaluate the rheology of the crust and the depth of magmatic sources. Scientific results highlight the presence of a high heat flow area (>100 mW m^2) in the western sector of Campania and Tyrrhenian basin, which is linked to the rising of the Moho at about 20 km of depth and to the migration of magma at shallower

levels. This process occurred since 1–2 millions years [3,9,13,109]. We have remarked that the fluid circulation (advection) supplies the main contribution to the heat transmission to shallow layers (1–2 km of depth). Advection processes are mainly developed at Ischia and Campi Flegrei, which show geothermal gradients of 150–200 °C km^{-1}, while they are less vigorous at Vesuvius, where the gradient is roughly 30 °C km^{-1}. This fact is mainly dependent on the different types of magmatic feeding systems at individual volcanoes. The dynamic of Campi Flegrei and Ischia, with uplift and subsidence periods, and their high geothermal gradients, can be related to the presence of shallower (2–4 km) and still hot magmatic sources [56,65,107]. This feature is better constrained by the results of geological and geophysical analysis at Ischia, while at Campi Flegrei the presence of shallow magma bodies (less than 7 km) is still debated. On the other side, the shallow magmatic structure of Vesuvius is characterized by a cooled system of dikes, which supplies a negligible amount of heat at the surface. The heat propagated by efficient convection is possibly concentrated close to the crater axis, while the larger hot fluids circulation is mostly confined in the carbonatic layer. Despite the high temperatures recorded at shallow depth and the occurrence of both water and vapor dominated systems, at Campi Flegrei and Ischia, the research for geothermal exploitation was abandoned, after 1985, for some technical problems and, much more, for social and political reasons. The reason why exploitation was not pursued despite the recognized high potential is likely due to the fact that, at that time, geothermal energy was not seen as an 'alternative' (renewable) energy, but rather as one of the energy sources, at the same level of gas and oil, with which it should be economically competitive, without any added value related to its 'cleaner' and 'renewable' character. Anoher problem was probably to ascribe to the fact that Mofete and San Vito areas, in that period, were becoming much more urbanized, so that it would have been problematic to adopt a large plant model development like in Tuscany. Nowadays, the technical problems, related to the high fluids salinity of the hot reservoirs, are overcome, thanks to the innovative technology applied to the geothermal plants [131]. Furthermore, now to geothermal energy, like the other renewable, is recognized a high added value with respect to more polluting, hydrocarbon sources, overcoming purely economic considerations. The option to invest on geothermal energy in the high heat flow area of south Italy and Campanian volcanic district will obviously depend on the policy of the future national and regional plans for energy, which, at the moment, is not well defined yet. We have shown, anyway, the very high potential of Ischia and Campi Flegrei geothermal areas, by using the volume methods, whose reservoirs have a total potential recoverable energy (thermal and electric) of about 17 GWy. Taking into account the extension of the urban settlements of the investigated areas, the features of natural landscape, and the characteristics of the geothermal reservoirs, the planning of small size power plants (1–10 MW) would be appropriate both from a cost-effective and from an environmental point of view. The Campi Flegrei area will be target, in the next years, to CFDDP (Campi Flegrei Deep Drilling Project). The project will consist of two drillings located in the eastern sector of the caldera, the first (pilot hole) reaching 500 m of depth and the second down to 3.5 km deep. This large international drilling project will further improve both scientific information on volcanic mechanisms at Campi Flegrei caldera, and the knowledge about related geothermal systems for the whole depth extension of aquifers, down to the supercritical temperature layers.

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